TRANSACTIONS
OF THE
AMERICAN INSTITUTE
OF
ELECTRICAL ENGINEERS,

JANUARY TO MAY, 1907.

VOL. XXVI, PART I.

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS,
33 WEST THIRTY-NINTH STREET,
NEW YORK, N. Y., U. S. A.
1908

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A paper presented at the meeting of the Boston Branch of American Institute of Electrical Engineers, Boston, Mass., January 9, 1907.

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GAS-ENGINE REGULATION FOR DIRECT-CONNECTED UNITS

BY CHARLES E. LUCKE

The speed of an engine may be expressed in revolutions per minute, or in terms of the linear velocity of the crank-pin in feet per minute. Revolutions per minute is rather more indefinite than crank-pin velocity in feet per minute, because feet per minute is accepted as not simply a measurement for a minute of time, whereas revolutions per minute more frequently is. Revolutions per minute may mean half the actual number of revolutions completed in two minutes or twice the number of revolutions completed in one-half minute, or it may mean the momentary rate of completing a revolution without any implied time. As there is a possibility of a lack of agreement on the implication in the term revolutions per minute, I should prefer to define the engine-speed in terms of crank-pin velocity in feet per minute, which can be expressed momentarily for any period of time, and does not imply any particular time. This velocity so expressed is the integral of the accelerating forces with respect to time, and in fact may be so defined according to the laws of mechanics.

The problem of regulation is really a problem of force balancing, and there are always two forces or two resultant forces in question: one a driving tangential force on the crank pin, the other a resisting tangential force at the same place. When these two forces are equal the acceleration is zero, and its integral, the engine-speed, is constant. If these forces are unequal there is a real acceleration, due to their difference, either positive or negative, and the engine-speed changes. The problem of regulation resolves itself into a demand for a balancing of forces at the crank pin after the desired speed is once attained. The exact solution of this problem is impossible and always will be, regardless of the type of engine or the conditions of operation. While it is impossible ever to keep the acceleration zero, and the actual engine-speed constant and of predetermined velocity, it is by no means impossible to keep the mean of these driving and resisting forces equal for certain periods of time, and the mean resultant speed any constant value desired. The prime variable in the problem is the resisting force, generally expressed in terms of load; but as load does not accurately describe actual resisting force, regulation cannot be directly studied from load alone and load must be resolved back to force. Practically all of the work that has been done in the solution of this problem of regulation in practice has concerned itself, either directly or indirectly, with the problem of securing a mean of equality or an equality of mean forces for some time-period, and a speed limitation by introducing heavy rotors.

This sort of study is decidedly useful but it does not give as clearly the nature of the problem or the available means of its solution as does the other point of view, which calls for a comparison of actual momentary forces and not mean forces, and further may lead to misinterpretation of results obtained. The problem of regulating steam engines has been discussed for many, many years; the problem of regulating gas engines for comparatively few years. By regulating I do not mean merely the preventing of undue and dangerous speeds, but the problem of securing uniform crank-pin velocities. There really existed no such problem calling for solution by mechanical engineers until electrical engineering developed a demand for a dynamo driven at a constant crank-pin velocity. The demand for this close regulation, therefore, is recent, but more recent still is the development of the large commercial gas engine. The methods and means for accomplishing regulation of steam engines have been very fully discussed, although the problem is by no means solved. There are many papers written on the subject, and a few of these will be examined. In general, however, they present limited data and only a part solution of the problem. An analysis of the problem of regulating steam engines will show it to consist of a few elemental problems, each equally important, some interdependent and some dependent. Some of these elementary problems are precisely the same for the steam engine as for the gas engine, and it is desirable that those interested in solving the gas-engine problem should have a clear understanding of what has been accomplished in the regulation of the steam engine. It will be found that a good many of the steam-engine problems have been fairly well solved, and this experience can be applied directly to the gas engine; but there are certain characteristics of the gas engine which must be separately treated and which differentiate its regulation problem from that of the steam engine.

Among the numerous papers on regulation and engine governing, all the early ones are concerned with governors. Until about 1898, when parallel operation of alternators became an important problem, it is surprising what a large amount of the literature reveals the idea that engine regulation is a problem of governor design. While up to that time this may have been more or less justified in view of the kind of regulation necessary, it is no longer the case; governor design, important as it is in limiting mean speeds and keeping mean speeds at high and low loads close together, is to-day only one factor in solving problems of regulation calling for uniform crank-pin velocities. Following two or three years' strenuous experience in regulation of steam engines for driving alternators in parallel, there appeared a remarkable series of papers before the American Society of Mechanical Engineers and the American Institute of Electrical Engineers setting forth the problem and giving some of the experience gained.

It is rather a noteworthy fact and coincidence that during the same period the gas engine as a competitor of the steam engine for general power purposes came into rapid development. At first economy was sought, and found; then life and low maintenance, which to-day is still a problem, together with gas-engine regulation for electrical work and the design for special service of special gas engines.

An examination of the early papers on governors will show that the design of masses developing centrifugal and so-called inertia forces for controlling valve-gears is fairly well understood. Barring the unknown elements of windage, friction, and valve-gear resistance, the problem is one of simple mechanics. The papers on steam-engine regulation show considerably more concerning the problem. Some of the important ones are worth a review, but first a few elementary principles will clarify the situation.

Every engine has some form of valve-gear. This valve-gear is intended to distribute steam in steam engines, to measure air and gas in gas engines, mix them, distribute the mixture, ignite it, and then more or less expel the products. This valve-gear, in engines intended for speed regulation, is adjustable either wholly or in part. The adjustable part is adjusted to enable the engine to do an amount of work commensurate with the resistance or load. A certain number of strokes is necessary for a complete cycle of operations. When the work done by the engine in this complete cycle equals the resisting work or the load, the engine will always have at the end of each cycle the same speed as at the beginning, however it may vary during the execution of the cycle.

A change in the position of the valve-gear will change the amount of work the engine is capable of doing by a change either in the steam distribution or in the handling of explosive mixtures. If the engine is to be commercial, the first requisite is that the amount of work the engine is capable of doing must be dependent upon and determined by the position of the adjustable part of the valve-gear, and that for any given position of the valve-gear, regardless of all previous positions, the engine should be capable of doing the same amount of work every time the gear reaches this position. The amount of work done by the engine is proportional to the area of its indicator card, so that the first requisite for an engine capable of close regulation is that for any given position of the valve-gear there must always be produced the same area of indicator card, and for any other position a different indicator card, different in area, and possibly, although not essentially, different in form. To fix the position of the adjustable valve-gear there is but one principle employed, and that is to leave it to the control of the centrifugal force acting through the governor. The centrifugal governor contains elements which have fixed positions for every speed. These elements are connected with the valve-gear so that it will have a fixed position for every different speed. With this combination, therefore, of a governor and valve-gear having a fixed position for every speed and an engine-control valve, igniters, etc., giving a fixed amount of work and a fixed indicator card for every position, there will result a mechanism in which the amount of work done per cycle by the engine will depend upon the speed. It is always the same at any given speed and cannot be changed without first changing the speed.

Different designs of governors containing different distributions of the masses, different fixed speeds, and arrangements of parts differ only in their ability to move the valve-gear a certain distance against a certain resistance in a certain time with a given speed-change. It is a problem of simple mechanics with a few unknown elements to design a governor that will, with any given change in speed, 1%, 2% or x% above or below the mean or average for the cycle, move any valve gear, however strongly it may resist, through any distance it may be necessary to move it, and as quickly as may be necessary. It may be assumed as entirely feasible, and not by any means difficult, to design a governor that will accomplish any valve adjustment in as short a time and with as small a speed as may be desired. There must be, however, a speed-change before the governor gear can move, and if the engine is capable of doing a constant amount of work per cycle for every governor position the amount of work per cycle it can do will depend upon the governor positions or speed. The mean speed for the cycle will be constant when the work of the cycle done is equal to the resistance work; therefore, for an absolutely steady load, in which the resistance per cycle is equal to the effort of the cycle, the mean speed will be constant and the governor stand still holding the valve-gear still.

To be strictly correct, the above statement should be modified because centrifugal governor position does not depend upon the mean speed for the cycle but upon the actual momentary speed, together with the inertia, friction, etc., of its parts and attached gear. If the work done per cycle is exactly equal to the resistance work for the cycle, then the mean speed will be constant, but the actual speed during the cycle may vary very much. Consequently, the valve-gear may change position during the cycle, which may or may not have, but probably will have, some effect upon the work to be done. To stand perfectly still all the time, the governor must be subject to a constant speed. This can be obtained only with a persistent equality between the driving force and the resisting force, irrespective of the work per cycle. Should the forces change throughout the cycle, the governor position will change, cylinder distribution change, and there would be a continual changing of work done, alternately increasing and decreasing. This is all due to the fact that the crank-pin forces throughout the cycle do not maintain equality and the valve-gear and work done per cycle depend, not on mean speed, but on actual speed in every instance, which is a consequence of the equality or inequality of the two crank-pin forces. With a centrifugal governor, therefore, even if the engine were capable of giving the same area of cards for every governor position, there cannot be a constancy of speed with a variation of resultant crank-pin force throughout the cycle. The governor may be damped; that is to say, it may be made less sensitive to speed changes either by dash-pots or other devices, in which case it becomes, not a simple centrifugal governor, whose position depends upon actual momentary speed, but a modified centrifugal governor whose position depends upon a sustained speed or mean sustained for some definite length of time. For such a governor to be perfect in its modifications it should have a position consequent on the mean speed for the cycle and not upon the actual momentary speed at any instant. If it had a position depending upon the mean speed for the cycle, then the valve-gear would stand still when the work done was equal to the load for the cycle, regardless also how the actual speed may have changed. The actual speed in such a case will change throughout the cycle, but the mean will be constant for the entire cycle and a predetermined speed reached at the end of every cycle with no undue hunting of the valve-gear from an over-sensitive governor in combination with a widely varying difference between widely varying crank-pin forces. If there were an actual equality between the driving force throughout the cycle such damping of the governor would be harmful instead of beneficial.

Since the valve-gear position in any case depends upon the governor position, and this upon the speed, it is certain that the valve-gear will not have the same position for high and low speeds or at the same time when little work is being done the speed cannot be the same as when much work is being done, the amount of work in each case being dependent upon the position of the valve-gear. In an engine producing the same indicator card for any position of the governor gear, which is controlled by a centrifugal governor, the no-load speed must be higher than the full-load speed, though each mean cycle speed may be constant if the load is constant.

If the actual load varies from time to time throughout the cycle of the engine, giving the mean load a constant value for the cycle, the effect will be the same as that obtained with a constant actual resistance and a more widely varying actual effort, so that to prevent an untimely change in the valve-gear position due to a momentarily changing governor position, as a result of this crank-pin force discrepancy, the centrifugal governor will have to be a modified centrifugal governor of the type that aims to maintain a fixed governor position for the mean speed of the cycle rather than for the actual speed. The modification of a governor to secure this aim, as was mentioned above, of the dash-pot order, involving some resistance to its motion, or it may be a long belt that will take up any flapping and stretching momentary changes, driving a governor having considerable inertia—in any case the actual speed-change due to discrepancy between the forces driving and resisting may be reduced by fly-wheel inertia. This is really all that a fly-wheel does in an engine. It plays no part whatever in the adjustment of the equality between the work and the load, but reduces the actual speed changes due to disturbing differences between the driving and resisting forces. No matter how big the fly-wheel, these speed-changes will exist and last for just the same periods of time as the difference between the driving and resisting forces. Pure inertia governors have not a steady position dependent upon the speed; they are dependent on the rate of speed-change for their motion, and are useful only in connection with centrifugal governors, to bring about a quick change in valve-gear.

It has been said that the design of these governors to accomplish the desired motion of the valve-gear any instant of time, regardless of resistance, is a simple method. It is, if all the elements are known. Books on mechanics enable us to equate resisting and driving moments in which the forces and loads, centrifugal forces, valve-gear inertia, pin and bearing friction, and possibly steam or gas friction, and windage. It is possible to find all of the existing windage. In some recent tests in the laboratories at Columbia University, I have been able to show that the motion of the governor is in some cases not more than one-half that found by neglecting friction and windage in the governor itself. The other elements unknown are valve-gear inertia and mechanical friction, but it should be possible to evaluate these by simple test, although very little data on the subject are in existence. Even with all these elements known, it may be extremely likely that cases will rise calling for very large governors due to a desire for prompt action against considerable resistance on the part of the valve-gear, having a considerable motion between full-load and no-load positions. To avoid making these very large governors, the indirect system of governing has been developed in which the governor controls no more than a pilot valve, which in turn distributes fluid pressure to pistons controlling the gear proper. These pistons, with their pilot valves under governor control, involve another complication in arrangement, which, however, is for the sole purpose of avoiding too large sizes in the governor, but which plays no part in the regulation proper except moving the valve-gear as a simple governor might move it. In all these devices the position of the piston should coincide with the position of the governor, or, to put it otherwise, with rapidly varying actual forces and constancy of mean work, the piston-position should be constant and related to the mean speed for the cycle, while in this case the governor position may actually vary as it will.

With a constant load, the valve-gear attached to the governor may be at rest or in oscillatory motion, depending upon whether there is a difference between the actual forces, driving and resisting; whether the governor and valve gear move as a result of actual speed or a sustained or mean speed for the cycle. The discussion so far applies equally well to the steam engines and gas engines, and so far as the governor itself is concerned with its connection to the valve-gear, direct or indirect, simple centrifugal or modified centrifugal, with or without inertia elements there will continue to be no difference between the steam engine and the gas engine. So much of the regulation, therefore, that depends upon governor and fly-wheel design itself is absolutely the same for steam and gas engines, with possibly one exception, that of a simple governor taking on momentarily new positions, due to actual speed change as a result of momentary force-difference, which might appear that for the gas engine or the steam engine these force differences shown by the turning effort diagram may be more inconsistent for one than the other; as a matter of fact they are not except in special cases. It is after the valve-gear has moved under the influence of the governor, either from a sustained speed-change or momentary speed-change, direct or indirect, that the real difference between the steam engine and the gas engine is found. There is a slight difference that will be met with in the constancy of the indicator card for a fixed gear position. All the steam valve-gears, will give absolutely constant cards for fixed governor positions, while only the best gas engine can do this. The cycle of operations in a gas-engine cylinder or steam-engine cylinder occurs in a certain order and the control gear never affects all the phases of the cycle. If an adjustment is made after the susceptible phase has passed, no results will appear until all other phases have been completed. The indicator card of the steam engine can be affected positively during steam admission only, but there are cases in which the compression line will be correspondingly affected. If the governor should move during the admission period the admission may be immediately affected, and a change of effort immediately follow within the lapse of part of one stroke. With a single-cylinder, single-acting steam engine, after cut-off, the governor can have no effect. Expansion must be completed, exhaust, and compression, so that if the governor moves the valve to the new position with cut-off, something over a stroke and approaching two strokes may elapse before a change in effort can occur. For this reason no single-cylinder, single-acting steam engine is employed for close regulation. By using a double-acting or two-cylinder engine one stroke can be cut out of this period which must elapse, or approximately one. By using more than one double-acting cylinder it becomes possible still further to reduce the cylic time, which must elapse between a change of valve-gear and new effort. The common type of large power-station engine is two cylinder, compound and often twin, giving four double-acting cylinders at some undetermined crank-angle, so that only a fraction of one stroke will have to elapse after a movement of the valve-gear before a change of effort, usually quite a small fraction.

The four-cycle gas engine may be regulated by the hit-and-miss governor, which is out of the question for close regulation since there is absolutely no attempt to graduate the effort. Next, there are throttling governors, which vary the amount of mixture by throttling the suction. There are others which admit a full charge during suction and expel part of it at compression by holding the valve open. Still another class, including oil-engines like the Diesel and Hornsby, admit fuel at or near the end of compression, and govern by varying either by the time of the injection or its length, generally the latter. Two-cycle gas engines of the Korting type may govern by acting on the suction of the gas pump with a throttle or delayed closure by any of the devices used on four-cycle engines, or it may govern by bleeding the charge in the gas chamber between the pump and motor cylinder. In both two- and four-cyle engines there may be an adjustment of the igniter. For reducing the time that will elapse between the valve movement and the beginning of a new effort the action should take place as late as possible in the cycle, which will give the effect as early as possible in point of time. For this reason a delayed opening on suction will be better than suction-throttling by a fraction of a stroke, and correspondingly the igniter action will be as prompt as affecting the admission as the steam engine. Equally prompt would be a fuel injection into compressed air at or near the end. No gas engine uses this. Unfortunately, however, for any igniter action, even a slight change will affect the economy and the range, is practically in only one direction. If the igniter is set right for economy, governor action can take place only to make it late and not to make it earlier with the proper effect. Making it late will reduce the effort and so will making it early, whereas an increase in effort is necessary in using this arrangement for regulating. In order to have a proper range for regulation by the ignition, the ignition should be normally set between properly early and very late, which gives poor economy. In any case where ignition is not used, as the beginning of a new effort, it may be assumed to take place on the beginning of combustion or the expansion stroke; the entire compression more or less must elapse between the valve gear at the charge and this beginning of combustion, a little less than a complete compression for delayed closure of the suction valve and a little more for the throttling action. In general it seems impossible to reduce the cycle of time to less than one stroke.

With this cyclic time it is useless to attempt to govern closely any engine with less than two double-acting, four-cycle cylinders, or one double-acting, two-cycle cylinder. It is useless to put a very sensitive governor or one of the highly refined inertia type on an engine that has been proved to be not worthy of it in the above mentioned respects.

A number of valuable papers on some of the phases of this regulation problem that are common to steam engines have appeared and a few of them will be examined.

Keilholtz: *A. I. E. E., October* 1901. In this paper a method for calculating the turning-force diagram is given, and the time, speed, and consequent angular variation from uniform rotary motion are calculated and experimental determinations reported. The paper is elaborate and involves a number of assumptions to simplify the work, but shows within the limits of experimental error and under conditions assumed it is possible to calculate true speed and to measure it so that the two results agree within the limits of experimental error. It is important to note, however, that the paper is confined to the case of constant resistance, equal to the mean effort, and the results depend for their value on the validity of these assumptions. Nothing whatever is determined concerning the effect of a fluctuating periodic load having the same constant mean, nor of the effects of load changes, nor the different speeds for different loads, nor the adjustment of effort and resistance by a true centrifugal governor, (whose position depends upon actual momentary speed), nor of a similar effect with the governor adjusted so that its position is determined for the mean speed for the cycle.

Slichter. Slichter notes a variation of speed: first, due to a change of load in which the average speed changes; secondly, irregularity throughout any given revolution or cycle while the mean speed is constant. He states that the adjustment of the mean is altogether a function of the governor and then drops the subject without pointing out the fact that no governor can accomplish this with a difference between driving and resisting efforts, if it is of the type whose position depends upon actual momentary speeds. The rest of Slichter's paper is taken up with the fly-wheel effects in reducing angular displacement from the mean or constant velocity positions with crank-pin force differences. The work is directed mainly towards alternators working in parallel, and the first problem for the solution is the determination of the crank-pin or pole displacements from true mean position, which will limit the cross-current to 10% of full load. In the course of his work he assumes the effort curve to be sinusoidal, which permits the development of a formula for a fly-wheel weight to limit the displacement. An example is worked out to illustrate the formula. Slichter however, aside from the errors introduced by taking the effort curve to be sinusoidal, makes the further assumption that the mean resistance is constant and equal to the mean effort. In other words, constant-load conditions only are discussed. He does however, make one important point, that when the alternators by any accident or fault of design get out of phase even slightly the actual resistance will be undulatory, although the mean may be constant.

Berg. Berg's paper is almost entirely electrical, and is concerned with the electrical conditions for parallel operation of alternators. The main feature with respect to regulation brought out in this paper is the pulsation of actual resistance with the constant mean when the alternators are slightly out of step, which is due to unequal momentary speeds of different machines in parallel, and which may be exaggerated by steam-effort impulses. It is not clearly pointed out that the real cause of exaggeration of these speed conditions is the fact that an alternator, taking positions due to momentary speeds, may be admitting steam in a pulsating way throughout a cycle, due to governor jumps when differences beween the actual effort wave and pulsating resistance becomes greater as the crests of the two waves may become opposed. The remedy observed is the use of a governor registering mean velocity for the cycle, and holding the valve-gear to the proper position for that mean. The means suggested by Berg is a dash-pot which is one of the ways of attempting to secure a mean velocity governor.

Steinmetz: *A. I. E. E., March* 1902. Steinmetz's paper is concerned with the problem of regulation with parallel alternator operation, and he notes three conditions to be examined: first a permanent change in speed due to a change in load. He points out here that there will be a different speed for every different load, the load, of course, being in any case a constant. This is an essential characteristic, as noted before, of centrifugal governors and their effects on the mechanism. Secondly, a temporary change in speed due to a change in load. In this connection he points out that on a change of load it is impossible for a governor to adjust the effort to the new resistance without the lapse of a considerable time. This causes a corresponding excess or deficiency of speed before the adjustment is accomplished. Thirdly, the periodic change of speed during "each revolution," which, of course, would be better read in "each cycle" as in some engines the cycle is not accomplished in one revolution. Steinmetz shows in this paper how important for the proper distribution of load between two alternators is this feature of having a different speed for every different constant load, and that a permanent drop in speed with increase in load is desirable. The absolute impossibility of a constant turning-effort diagram is shown, but the desirability and possibility of reducing variation of the turning-effort diagram by cylinder combination and crank-angles is pointed out, as well as the effect of reducing speed-changes for a given variation of effort by the fly-wheel. The periodic variation in speed, due to actual variation between effort and resistance, is assigned by Steinmetz as the cause of the hunting of alternators and synchronous apparatus, and he says that the effects are aggravated by the use of heavy fly-wheels. Steinmetz notes two kinds of hunting between alternators: forced surging, and cumulative or resonating surging. Forced surging is that due to momentary crank-pin-force differences, and cumulative surging is that due to certain electrical characteristics of the circuit, or may be assigned to the mechanical construction of the engine, especially the governor if the governor has a tendency to jump, which is explained as a tendency to take on a position due to momentary velocities.

Emmet. Emmet's paper is entirely concerned with parallel operation of alternators driven by steam engines and the effect of governor damping on the reduction of cross-current or surging. The paper gives examples of engines operating in Philadelphia and Boston. In Philadelphia it was found that the governor was in constant motion even with constant mean load, and that the indicator cards were consequently continually varying under the same constant load, as might be expected. The governor, when blocked, held the valve-gear in a constant position, and in this way absolutely constant cards were obtained. This shows that there was no fault in the governor and valve-gear as such, but rather that the load, although apparently constant in its mean value, was a pulsating one and the governor and valve-gear took momentary positions due to momentary speeds, due in turn to momentary force differences at the crank-pin. The fact that the surging was worse at times than at others is simply an indication of that fact noted above that while the mean load was constant and governor jumping could result with variation of effort, the pulsating load gave a wave of force, the crests of which sometimes coincide with and sometimes oppose the crests of the effort wave, giving, therefore, at times, a greater force-difference and at other times a less force-difference than with constant resistance. The trouble was cured by dash-pots on the governor, which had the effect of preventing the governor taking positions due to momentary velocities, and making it rather tend to assume a position due to mean velocity for the cycle. It was found in Boston that while similar surging existed and became less by the use of dash-pots, it could not be cured even when the dash-pot was strongly resisting the governor motion, as it permitted the mean speed to vary considerably. In this case, therefore, it appears that dash-pots may fail to accomplish the result of making the governor take a position due to the mean speed of the cycle, but, on the contrary, may actually resist any motion on the governor so that it becomes no longer a governor. This led to what has been called the "time-relay dash-pot," which is really no more than an improved form of modified centrifugal governor to make it more nearly fixed in position for the mean speed for the cycle without resisting an adjustment to a new mean. It is also interesting to note that Emmet reports a light fly-wheel better than a heavy one for successful parallel operation.

Rice discussing Emmet. Rice points out that a method of adjusting the fly-wheel weight by the allowable generator wheel displacements and the turning-force curve for the engine for constant load, but does not consider a variable load curve either periodically or irregularly variable.

Also on governors he states that they must have certain characteristics: they must be adjustable for speed-position to allow voltage adjustment and load distribution between machines; they must be adjustable with damping; they must have power enough to control speed in spite of damping; they must be switchboard controlled.

There is no discussion whatever in connection with this governor question by Mr. Rice of the period that must elapse between the governor movement and resultant effort change, nor of the limitations imposed by the cycle of operations on this period.

Seymour discussing Emmet. Seymour refers to the misapprehension of the specific nature of the requirements for parallel operation under which salesmen for engines and generators, as well as purchasers of the apparatus, may be laboring. He states that close regulation is generally interpreted to mean small differences between mean speed at no load and at full load, and points out that a small difference between these mean speeds is not a requirement of alternator parallel operation, and in fact it is better for load distribution between alternators that this difference be large comparatively. He next considers fly-wheel weights and says that a fly-wheel heavy enough for a uniform effort, when there is a discrepancy between driving and resisting forces, will increase the trouble from generator surging, referred to as "cumulative" by Steinmetz. The importance of noting the period of governor jumps, and the period of the varying resisting forces coinciding with the variable effort-crests, when the alternators are slightly displaced, is given some attention. The impossibility of correcting faults by governors alone is also pointed out when undulatory resisting-crests oppose undulatory effort-crests. Seymour does not state it quite this way, but this is in effect what I understand he means. He then gives some experimental data on the regulation of engines built by his firm.

Scott discussing Emmet. Scott first draws a parallel between parallel operation and two engines driving generators by gear wheels on the same shaft. Scott also notes the importance of the periodicity of governor jumps synchronizing with the periodicity of the maximum difference between driving and resisting forces, shown by the effort and resisting force; but as in the case with Seymour he does not state the situation quite this way. The point he makes is the special importance of noting the periodic nature of the electrical load in certain cases even when the output is constant, and gives examples of an alternator, which worked satisfactorily on a lamp load but would not at all with a synchronous converter in the circuit.

Mershon discussing Emmet. By curves between speed and load, when load is constant, Mershon shows the importance of having a considerable difference between full load and no load for proper distribution of load between the machines, and shows by variation of these curves why the distribution may be more stable at one load than at another.

Steinmetz discussing Emmet. Steinmetz points out that a heavy fly-wheel is bad only because by reason of its great inertia it permits the governor to overrun resisting synchronizing after once displaced.

Behrend discussing Emmet. Behrend refers to two alternators abroad, driven from the same engine shaft, which would not run in parallel at all. This is a striking example of the periodic nature of an electrical load and shows the importance of realizing that electrical circuit characteristics are matters of as great importance in parallel operation as engine characteristics, and that a failure to operate satisfactorily in parallel cannot always be traced to the engine regulation.

Slichter: *A. S. M. E.*, 1902. Among other matters taken up similar to those in his other paper in the Institute he lays particular stress on the computation of displacement of the alternator by inconstant turning effort and shows that the cross-currents and magnetic pull on the rotating system depend upon the amount of displacement. The difficulty is greatest with the greatest number of poles. He refers to a paper by Longwell before the Engine Builders' Association on the "Synchronization Torque of Generators" due to the displacement from the mean position where the torque is proportional to the displacement. The displacement is greatest also at the time when the disturbing effort is greatest, so that the two effects of synchronous torque and displacing effort torque are additive, and being additive are cumulative, helping to put the generators out of step. Some examples are given involving turning effort curves and computations of displacement.

Longwell discussing Slichter. Longwell first refers to a paper by Rosenberg, engineer for Korting Bros., gas engine manufacturers in Germany, in the *Electro Zeitschrift*, 1902, in which the cumulative effect of the magnetic pull and the disturbing irregular turning forces are shown to be impossible of prediction, and dependent upon the type of engine among other things. Mr. Longwell concludes that no mathematical treatment of this subject is adequate. This is true because the effect is partly mechanical and partly electrical and not all of the variables, either electrical or mechanical, are known.

Astrom, A. S. M. E., 1901. "Fly Wheels and Angular Variations." First there is given a complete calculation of turning effort and the effects on turning effort of the mechanical forces, due to reciprocation parts, rotary parts, gravity elements, and the connecting rods which partly rotate and partly reciprocate. This concludes with a number of turning-efforts diagrams and variable-load curves for pumps and compressors, enabling the crank-pin force difference curves to be plotted. The coefficient of fluctuation of speed for different classes of machinery are given in fractions of the mean, but it is pointed out that as machines of the same class with the same coefficient of speed fluctuation do not work equally well, it is evident that a small coefficient does not assure satisfactory speed regulation. The consequent displacement from the mean position is then developed as a substitute for the coefficient mentioned in fixing a unit regulation, and is shown to be the result of double integration of the force curve. Some turning-effort curves are given for steam engines at full load and light load, and the effects of different crank-angles on the uniformity of effort together with the reduction in fly-wheel weight for equal regularity of motion computed. Astrom makes only one reference to load changes and makes no attempt whatever to get results in speed changes.

Abbot discussing Astrom. Abbot gives a complete calculation for a steam engine, in which the coefficient is as small as one-three-thousandth and the displacement 2.5 electrical degrees when calculated by the usual method of turning-effort diagram with mean effort equal to mean resistance and resistance constant. No reference whatever is made to variations in resistance.

Paper by Dr. Franke, on the coefficient of irregularity. L' Eclarage Electric. In this paper there is a discussion concerning the coefficient of irregularity or speed steadiness for alternating-current and direct-current machines, and it is stated that this unit is a very satisfactory one for judging a direct current machine, as it represents very nearly the variation in voltage and the flickering of the lamps. 1/200 is considered to be good, and as low as 1/80 satisfactory, while 1/65 is considered impossibly bad. It is pointed out that with a single-cylinder, four-cycle gas engine 1/80 and 1/100 should easily be obtained without abnormal fly-wheels and these machines can, therefore, be depended upon for satisfactory voltage regulation. No reference, whatever, is made to what will happen on the change of load; this is based on the usual method of calculation for constant load and mean effort. With respect to alternators: it is pointed out that if the coefficient is too small the result will probably be worse than if it is not small enough. He considers 1/200 quite satisfactory. It is pointed out that cross-currents tend to accelerate the lagging machine and retard the leading, and the accelerating force or magnetic pull depends not at all upon actual speed but on the displacement of the poles, and that heavy fly-wheels resist in bringing into its proper place a pole once displaced, although it would seem at first to be sufficient guarantee against displacement initially. Light fly-wheels are recommended as better than heavy ones, but there is no means given for judging their weights except the old rule of computation of constant resistance with variable turning effort.

Summarizing the variations of conditions entering into the regulation problem under the headings of load, effort, governor, fly-wheel, and valve-gears, we have the following:

Kind of load.

1. Load may be constant and equal to the mean effort.

2. It may be constant and greater than or less than the mean effort.

3. Load may be undulatory, having a mean equal to the mean effort.

4. Load may be undulatory with a mean equal to the mean of an undulating effort.

5. Load may be constant at a maximum.

6. Load may be constant at zero.

7. Load may suddenly change from one constant value to another constant value, up or down.

8. Load may suddenly change from an undulatory with a constant mean to another undulatory with a constant mean.

9. Load may suddenly change from an undulatory with a constant mean to a constant.

10. Load may change from any value to an undulatory with a constant mean.

11. Load may change from an undulatory with a constant mean to another undulatory with a constant mean.

12. Load may change from any irregular value to any other irregular value with no particular relation between.

13. The time at which the load changes may occur at the most favorable point of the cycle for a change of effort.

14. The time at which the load changes may occur at the most unfavorable point of the cycle for a change of effort.

15. The time at which the load changes may occur at the same point between most favorable and unfavorable point of the cycle.

Kind of effort.

1. The effort may be absolutely constant for full load and a maximum.

2. Effort may be absolutely constant at zero.

3. Effort may be constant at any value between maximum and zero

4. Effort may be regularly undulatory with a constant mean for each cycle.

5. Effort may be irregularly undulatory with a constant mean for each cycle.

6. Effort may be irregular with a constant mean for two cycles.

7. Effort may be irregular with a constant mean for no full number of cycles.

8. Effort may be that for a steam engine, single cylinder, with low or high inertia.

9. Effort may be that for a double-acting, single-cylinder steam engine with a low or high inertia.

10. Effort may be that for any number of cylinders of the double acting, simple, triple, compound, etc., with a low or

high inertia of any number of cranks spaced in any particular way.

11. Effort may be that for a single-cylinder, four-cycle gas engine, single acting, low or high inertia.

12. Effort may be that for a single-cylinder, single-acting, two-cycle engine, low or high inertia.

13. Effort may be that for a single-cylinder, double-acting, four-cycle gas engine, low or high inertia.

14. Effort may be that for a single-cylinder, double-acting, two-cycle gas engine, low or high inertia.

15. Effort may be that for a two- or four-cycle engine, single or double acting, with any number of cylinders, low or high inertia, with any number of cranks grouped at any particular angle.

16. The fly-wheel may be light or heavy with large or small mean diameter.

Governors:

1. The governor may be a simple centrifugal governor, taking a position corresponding to the momentary actual speed.

2. The governor may be a modified centrifugal governor, taking a position not due to the momentary actual speed.

3. Governor may be of a modified, centrifugal type, taking a position due to the mean speed for the cycle.

4. The governor may or may not have inertia elements to affect the promptness of the motion of the valve-gear independent of actual speed, but depending on momentary acceleration, positive or negative.

5. The governor may be large or small with ability to move the valve-gear through large or small distance in short or long periods of time, against large or small valve resistances.

6. All the simple, centrifugal types or modified centrifugal types with or without inertia effects.

Valve-gears.

1. Valve-gears may affect the cycle so as to change the effort immediately.

2. Valve-gears may be so designed as to affect the cycle only with the lapse of some part of the cycle or some part of more than one cycle.

3. Valve-gears may be heavy or light with or without gravity resistance in one direction, with or without gravity assistance in the other direction, with or without inertia resisting its motion with high or low frictional resistance through change of position.

To study adequately all the conditions appearing in this summary, including the unusually large number of variables under the five groups, more or less dependent, is a very tedious matter, but nevertheless worth while. I think, however, from the review of the papers given, it seems pretty clear what is the function and limitations of governors or fly-wheels. From the large number of turning-effort diagrams, steam and gas engines, the nature of this effort-curve and its change with load, cylinder combinations, grouping of crank-angles, different inertias and reciprocating parts, have become fairly well known. To those not familiar with such turning-effort diagrams of gas engines, reference may be had to Guldner, Haeder, Lucke, and numerous papers. A comparison of the gas engine, turning-effort diagram with that of the steam engine will show that it is possible to secure as regular an effort curve for the gas engine as for the steam engine; regular with respect to the number of fluctuations above or below the mean, and with respect to the value of the coefficient of fluctuation. That is to say, that the turning-effort diagrams for the gas and steam engine are equally good as computed under the constant load condition, and this is the only basis on which they have been computed. What happens when the load changes and before the governor has had time to balance the effort with resistance, will be different for the two classes of engine and different again for individual examples of each class.

The things that have not received much attention, or anywhere near adequate attention are:

A. The electrical effects in producing variables actual resistance at the crank-pin for constant bus-bar loads.

B. Cyclic interference between governor control and effort effect.

C. The speed-change due to load-change due to a period of unbalance exaggerated by cyclic interference and pulsating effects, which cannot be overcome by any refinement of governor construction and which are just as likely to require light as much as heavy fly-wheels on the engine, but which probably can be met in the gas engine by a change in valve-gear control functions or a change in cycle.

Just what can be accomplished along these lines can only be determined by plotting force diagrams representing driving and resisting forces for each moment of the cycle, and in connection with each force-diagram a consequent velocity-diagram obtained by the integration of the force or accelerating diagrams. The force used in this integration will be the algebraic sum of the driving and resisting forces of each moment, and if both are varying they may be additive or subtractive.

To illustrate this method of treatment the following sketches are presented, not as a solution but solely to illustrate the method of procedure. Fig. 1 shows the force-diagram and velocity-diagram for a steam turbine with a constant-resistance load. This diagram shows a full-load and light-load force and speed curve and indicates that the light-load speed is higher than the full-load speed and instead of being exactly constant are nearly so with constant mean. The effort curve on the turbine slightly rises and falls fairly regularly for a constant resistance, which is shown by the dotted line.

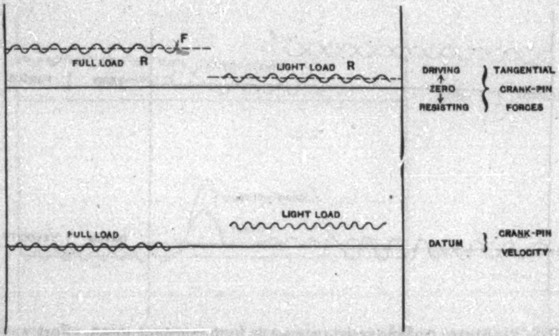

Fig. 1—Steam turbine resistance constant, effort pulsating constant mean

Fig. 2 shows a variable resistance of a wave-form nature and a similar waving effort, both with constant mean. The velocity-diagram for these conditions will involve greater waves than before or greater fluctuations above and below the mean, because the effort and resistance become additive at crests and hollows, even though the mean value of each is constant.

Fig. 3 shows force and velocity diagrams for a constant full load change to a constant light load with a corresponding jump in velocity during the period of governor action.

Such curves as these indicate clearly the fly-wheel effect, and show that it merely limits the maximum velocity during the period of unbalance and has no effect on the period of unbalance or the period of acceleration. These curves also show that the maximum velocity is attained after an acceleration when that acceleration has again decreased to the mean value. They will also show how the governor must override in its efforts to reduce a too high velocity to the required new mean value. If such curves are shown for steam and gas engine with their available effort-diagrams in place of these nearly constant turbine effort-diagrams, I think it will be easy to see how clearly the problem of regulation can be studied and also the effects of variable actual load at the crank-pin when they do or do not synchronize with the effort wave.

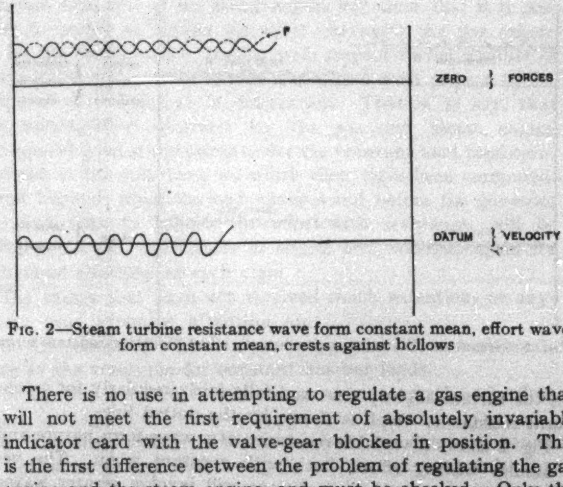

Fig. 2—Steam turbine resistance wave form constant mean, effort wave form constant mean, crests against hollows

There is no use in attempting to regulate a gas engine that will not meet the first requirement of absolutely invariable indicator card with the valve-gear blocked in position. This is the first difference between the problem of regulating the gas engine and the steam engine, and must be checked. Only the best gas engines will give such invariable cards. The next step is to run the governor with all valve-gear connected but with the engine at rest, the governor being driven from an external source to determine valve-gear positions at different speeds of the governor. This requires very accurate speed-measuring apparatus. The next experimental check is to measure the mean effective pressure obtainable at all different positions of the valve-gear, it being blocked during measurements and the engine held to about the proper speed with suitable resistance and the governor cut out. From this the speed horse-power curve should be plotted and there must be not too small a difference between mean speed at constant full load and the same at constant no load. The result should be checked by operating the engine with everything connected and a variable load. Every precaution should be taken to insure the governor operating valve from sticking either by tar or dust collection. The next important difference between the steam engine and gas engine regulation will come in as the result of cyclic interference in each. This requires calculation and experimental check to obtain proper data on the necessary sensitivness and type of governor fly-wheel effect, which should neither be too much nor too little in the light of the operation requirements.

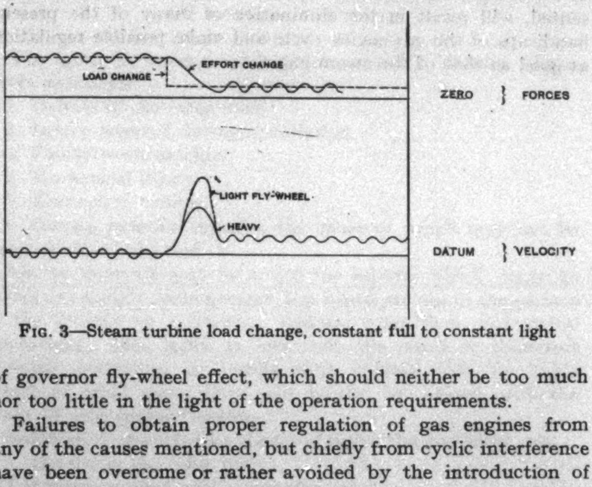

FIG. 3—Steam turbine load change, constant full to constant light

Failures to obtain proper regulation of gas engines from any of the causes mentioned, but chiefly from cyclic interference have been overcome or rather avoided by the introduction of flexible couplings, consisting of leather link, spring, friction slip joints, centrifugal devices, all of which are intended to allow the driven rotor to move at a uniform speed, even though that of the driving engine should fluctuate. These devices have never been used on large units and are by no means solutions.

Large gas engines are operated fairly satisfactory with twenty-five cycle alternators and the cyclic interference, while it is always noticable is not prohibitively bad. With 60-cycle work this is not the case, and gas-engine-driven, 60-cycle alternators must be so far pronounced unsatisfactory, though some are doing well. Considering the nature of the problem; its newness, its difficulty, and the more insistent demands of the public for economy of fuel, and ruggedness of construction than for close regulation up to the present time, I think that the gas engine has done extremely well. The wonder is, then, not that the gas engine cannot regulate as well as the steam engine, but that it regulates as well as it does. In the light of all this I feel that the gas engine has only just started on its career of usefulness.

In conclusion I believe that an intelligent examination of the nature of the problem of gas-engine regulation and the study of numerous diagrams, force and velocity, of the kind here presented, will result in the elimination of many of the present handicaps of the gas-engine cycle and make possible regulation as good as that of the steam engine.

A paper presented at a meeting of the Baltimore Branch of the American Institute of Electrical Engineers, January 11, 1907, in the Physical Laboratory of the Johns Hopkins University.

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UNDERGROUND TRANSMISSION AND DISTRIBUTION OF ELECTRICAL ENERGY.

BY CHARLES E. PHELPS.

The faults in underground cables naturally classify themselves as follows:

1. Defects in the cable itself.
2. Injury received during installation.
3. Faulty workmanship.
4. Mechanical injury.
5. Electrolytic action.
6. Certain external injuries, the cause of which may not be conclusively established.

And to these six may be added the injuries which occur to cables not strictly underground, but which are above the surface of the ground on poles, etc., making connection with aerial conductors. This latter is uniformly the result of imperfect covering protection, or results from contact with the cable sheath of aerial wires; they can hardly be classed with the faults of underground cables.

Referring to the other six classes of faults, the first three; viz.

1. Defects in the cable itself.
2. Injury received during installation,
3. Faulty workmanship,

should be sufficiently provided against in the contract for the cable and in the character of conduit construction, that they may be developed on the breakdown test which is invariably applied to a completed cable before putting it into continuous service. This test usually requires that at least double the ordinary working voltage shall be applied to the insulation of the cable; that is, between conductors and ground, for various periods of time depending upon the judgment of the purchaser and acquiescence of the contractor. The test should never be pushed to a point where the insulation is liable to be pin-holed by the strain of the test voltage, and experience has generally pointed to the continuance of the test voltage for from one to two minutes' duration, instead of thirty or more minutes which have often been specified. Under this test the defect should be developed and the obligation should, by contract, be imposed upon the contractor to make it good. If it should have been caused by any defect in the conduit construction the cable contractor would, of course, be blameless. The other faults:

4. Mechanical injury,
5. Electrolytic action,
6. D[illegible]cable above ground.

All these are of purely external cause.

In order to illustrate this feature more prominently, below is given a tabulated record of cable faults in this city for the seven years ending December 31, 1906, together with the lengths of cable in use in each year. This tabulation includes all classes of cables:

13,000 = volt alternating-current, three-conductor cable.
6600 = " " " " " "
2300 = " " " " " "
1000 = " " " two- " "
500 = " street railway feeders,
250 = " three-wire distribution,
Telephone cables from 5 to 400 pairs,
Telegraph " " 20 to 200 wire,

and various smaller cables used for burglar and fire alarm and other signalling purposes, including the police and fire alarm wires of the city. In fact the table includes injuries to all those classes of wires which are found to be necessary in the activities of any large and growing city. Summarized by classes of faults and by years, the table is as follows:

It should be noted in connection with the table above given that damage under head of gas explosions was not the immediate result of the explosion, but was caused by the falling of debris and burning gas. No cable has been directly injured from any gas explosion under observation. Also, that the damage under " Flood Water—Jones' Falls " was due to the carrying away of cables on temporary suspension under a bridge crossing Jones' Falls, by heavy timbers carried down by flood water.

Class	Nature of Damage	1900	1901	1902	1903	1904	1905	1906	Total
1	Defective cable...	—	1	—	—	—	2	—	3
2-3	Damage during installation.......	—	—	—	3	7	4	10	24
4	Damage by picks, bars, etc.......	—	2	6	6	13	27	4	58
4	Flood water, Jones Falls..........	—	—	—	1	—	1	—	2
4	Gas explosions....	1	—	—	—	1	—	—	2
4	Rats.............	—	—	—	—	—	—	5	5
4	By workmen in manholes.......	—	—	—	2	3	4	4	13
5	Electrolytic action	1	—	2	15	5	4	4	31
6	Cables above ground.........	—	1	1	—	—	—	—	2
7	Unknown........	—	—	—	—	—	7	1	8
	Totals.......	2	4	9	27	29	49	28	148
Feet of cable in operation at end of each year...............		106,779	236,266	470,154	708,152	853,948	1,246,443	1,535,294	
Fault per 1000 ft. of cable..............		0.018	0.017	0.019	0.038	0.034	0.039	0.018	

Summary of Cable Faults

Class	Nature	Number of faults	Per cent. of whole
1.	Defective cable..	3	2
2.	Damaged in installation...........................	24	16
3.	Mechanical injury....................................	80	55
4.	Electrolytic action....................................	31	20
5.	Cables above ground................................	2	1.5
6.	Unknown causes......................................	8	5.5
		148	100

The percentage in importance of each class of fault to the whole number is:

1. Defective cables..................... 2 per cent.
2. Damaged in installation. ....16 "
3. Mechanical injury..................55 "
4. Electrolytic action...................20 "
5. Cables above ground.............. 1.5 "
6. Unknown.............................. 5.5 "

This is for the whole period of seven years; the record of the year 1906, just past, during which time there were over 1,500,000 ft. of cable in operation, is as follows:

1. Defective cables	none
2. Damaged in installation	10
3. Mechanical injury	13
4. Electrolytic action	4
5. Cables above ground	none
6. Unknown	1

a total of 28 or $\frac{18}{1000}$ per 1000 ft. of cable in operation.

In considering the tabulations of cable faults, these data must be understood to show actual existing and not sporadic conditions; that not only do they cover a considerable period of time but they cover also a time during which progress in this particular branch of the art was undergoing great changes. A part of the time may even be taken as experimental In addition to this, the data for the years 1904 and 1905, shown in these tables, will suffer in its application to a normal situation by reason of the apparently high percentage of faults developed on account of mechanical injury.

Out of a total of 80 faults by mechanical injury for seven years, exectly one-half, or 40 of them, occurred during the years 1904 and 1905, although in 1906 there were but four, while the amount of cable in use was much greater.

This disproportion is easily explained by pointing out that during 1904 and 1905 all street improvements consequent upon the fire of February 1904 were carried out. Street lines and grades were changed, necessitating a similar change in conduits and of cables within them. A great many men were employed upon all sorts of work and naturally the underground system has to stand its share of damage.

In studying the list of cable faults you will see that, barring the sole element of human frailty, all the faults may be to a large extent anticipated, and in a large measure avoided. By analyzing these failures, you will find some definite reason for each of them to which a remedy can be applied. I do not intend to convey the impression that a cable system can be developed which will never be fault-proof, because the conditions under which it is operated are not those of a parlor game; but one has to deal with men and materials that are by no means perfect.

I can perhaps illustrate the conclusion which I desire to convey to you. Suppose, say 20 important companies on this continent engaged in the same character of electrical business were to keep accurate records of the performance of their underground equipment under actual operation, with clear explanation of the conditions surrounding and the effect of each cable fault; and suppose that all these 20 separate sets of data were available to each one of the companies concerned so that each would have, in addition to its own data, those concerning the cable performance of 19 other companies. Suppose now you had these data in hand, what would be the result? You would eagerly search out those of the companies which showed few faults where you were subjected to many of the same kind, and you would get in touch with them and learn in what particular they had succeeded where you had failed. In the same way you would be called upon to explain your successful methods to certain others who had failed where you had succeeded. This is a process which seems so easy, so simple, and so inexpensive when the great benefits that would accrue are considered, that it seems surprising it is not an almost universal custom. I cannot refrain from backing up this statement by saying that this spirit of coöperation and coördination is one of the important elements which has maintained the preeminence of the Bell Telephone Company in its particular field of operation, judging solely by results from the point of view of an outside but interested observer.

Before closing this paper I ask your consideration to a brief review of this particular subject which may really be termed the crux of the whole situation. Taking the cable faults in the order they appear on the chart, the first three:

1. Defect in cable itself,
2. Damage during installation,
3. Faulty workmanship,

should be covered by the contract for purchase and installation of cable, and they should be " smoked out " by the installation test before described. Owing to the fact that the factory test of cable before shipment is much more severe than the installation test, and that the factory test is made on the cable while submerged in water, it is more than probable that any fault developed in the body of the cable itself will be caused either during shipment or during installation.

It will generally be impossible to determine on light and power cables, which was the real cause, for the effect of the breakdown is to destroy the evidence entirely; the affected part of the cable will vanish to parts unknown.

Faults due to installation are in general due to four causes;

1. Defective conduit structure,
2. Reckless or improper methods of pulling cable into ducts,
3. Rough handling or too sharp bends in manholes,
4. Badly made joints.

I think it sufficient simply to enumerate these causes to indicate the prevention or remedy.

Faulty workmanship may occur either during installation or later, due to additional taps or connections being made to an existing cable. Here the remedy, aside from the employment of only skilled and careful workmen, is to provide a manhole suitable for the conditions under which this work is to be done. There should be plenty of elbow-room, and cleanliness is one of the best friends to the underground cable. Even in a city without sewers, the expense of consistent drainage of manholes by expensive methods is justified.

Mechanical injury may come from without through the agency of the energetic man with the pick who generally never works so hard as when he is hacking away at something he has no business to hack; or it may come by reason of improper use of the manhole by workmen; or from such an unusual source as the despised rat, which has been dignified by what I hope are five obituary notices in our exhibited list, under the year 1906.

I hardly feel able to point out any remedies against this prolific cause of cable trouble that have not already perhaps occurred to you, but there is one which comes from within and which often and unnecessarily results in trouble and is easily avoided. This, as is usually the case with internal cable troubles, concerns the manholes. I have myself recently seen inside the manholes of an important underground system where the cables therein were so run through the manholes that it is impossible for a workman to get to the floor of the holes without using these cables as a step ladder. This was the case, not in a single manhole, but in many of them. Apparently the manholes were built simply because every other underground system had them, and they exhibited utter disregard of their permanent use by the cable equipment for which they were built.

A paper presented at the 213th meeting of the American Institute of Electrical Engineers, New York, January 25, 1907.

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ON THE SUBSTITUTION OF THE ELECTRIC MOTOR FOR THE STEAM LOCOMOTIVE.

BY LEWIS B. STILLWELL AND HENRY ST. CLAIR PUTNAM.

The purpose of this paper is fourfold: 1, to record certain facts relative to heavy electric traction which have been established by experience; 2, to present calculations of relative costs of steam and electric traction in railway service based upon these facts; 3, to point out the transcendent importance of standardizing electric railway traction equipment as rapidly as may be consistent with progress; and 4, to raise the question whether a frequency of 25 cycles per second or 15 cycles per second should be adopted in railway operation by alternating-current motors.

Few subjects which are to-day engaging the attention of the engineering world are comparable either in scientific interest or in practical importance to the substitution of the electric motor for the steam locomotive engine. Three-phase and single-phase alternating-current railway motors are now developed to a point where they fairly challenge the steam locomotive, even in long-haul freight service, in which class of work the direct-current motor hitherto has found itself unable to compete with success. The direct-current motor has demonstrated impressively, and upon a large scale, its superiority to the steam locomotive, not only in operating single cars and short trains on lines of moderate length, but also in frequent and heavy passenger service in which the length of train is limited only by the length of station platform, while the motive power equipment far exceeds in power developed the limits hitherto established in steam passenger service.

On the Valtellina line and through the Simplon tunnel 70-ton electric locomotives with three-phase motor equipment, capable of developing a draw-bar pull of 28,000 lb., have displaced the steam locomotive, with results showing both marked improvement in service and substantial economy in operating costs. In the New York Subway, eight-car trains weighing 320 tons are in operation, equipped with motors developing during acceleration a tractive effort equivalent to a draw-bar pull of 55,000 lb.

The heaviest passenger locomotive used on the Erie system in 1905, weighs, exclusive of tender, 206,000 lb., of which 55.8%, or 115,000 lb., is effective on drivers. Assuming the adhesion to be 20%, such a locomotive exerts a draw-bar pull of 23,000 lb. The motors of the eight-car electric train of the New York Subway, therefore, exert a tractive effort equivalent to more than twice the draw-bar pull of this locomotive.

Managers and engineers of railways using steam are considering the possibilities of electricity. Naturally, the problem usually presents itself in reference to particular cases in which special conditions emphasize the advantages of electric traction; but a point has been reached in the development of electric railway equipment where it is evident that no absolute and permanent limits beyond which the motor may not go can be fixed; and it is not unreasonable to consider the possibilities of the electric motor not only in passenger service but also in freight service, not only in the operation of railway terminals, but also for the operation of railway divisions and even for trunk lines.

At the present time, what is needed is not prophecy but facts, and particularly facts demonstrated by experience. A study of the relative advantages of steam and electric traction should rest as firmly as possible upon results attained in practical operation. Facts thus established and available to date are insufficient to justify conclusions which in detail may not have to be modified, but it is believed that they are adequate to permit comparative studies leading to deductions, which, as a whole, may be relied upon.

The answer to the question: " Will it pay to electrify? " involves consideration of both relative earnings and relative cost of operation; therefore, before discussing the comparative expenses involved, it is pertinent to refer briefly, even at the risk of repeating what has been said in papers hitherto presented by others, to the more important factors which ocoperate in securing for electric traction an increase in earning power.

PASSENGER SERVICE FACTORS CONTRIBUTING TO INCREASED EARNING POWER.

The more important considerations which affect gross earnings are:

1. Frequency of service.
2. Speed.
3. General comfort of passengers.
4. Safety.
5. Reliability of service.
6. Increased capacity of line.
7. Frequency of stops.
8. Convenient establishment of feeder lines.

1. *Frequency of Service.* The motor-driven, interurban car operating upon scores of lines in competition with steam railway service has convincingly demonstrated its ability, not only to attract business from competing steam lines but also to create new business. In almost every case where such competition has been encountered by the steam railway, a large part, if not practically all of its local passenger traffic has been lost. In comparing results attained by the competing systems in such cases, it is impossible, of course, to state in terms of precision how far frequency of service is responsible for the remarkable results observed, since to these results a number of other causes also contribute. But without attempting to differentiate between these various factors, it is sufficient here to say that of the several causes contributing to the marked success of lines using electricity, the operation of train units or of single cars upon close headway is recognized to be especially attractive.

The advantages resulting from frequency of service become relatively less as the length of run is increased. It is recognized, however, that the operation of trains under close headway generally increases traffic, even where the haul is of considerable length, as shown by the experience of the Philadelphia & Reading Railroad in operating its fast trains upon one-hour headway between New York and Philadelphia.

2. *Speed.* The possibilities of operating by electricity at speeds exceeding the maximum which can be obtained safely in steam operation, owing to the elimination of unbalanced reciprocating

parts of the locomotive, is well-known. It was strikingly illustrated in the Berlin-Zossen trials by the attainment of a speed exceeding 130 miles an hour. These tests demonstrated the ability of electric equipment to operate at a sustained speed more than twice as great as that of our fastest express trains on runs of any considerable length, and exceeding by about 50% the maximum which can be attained even for a short distance by the steam locomotive with a reasonable degree of safety.

Even at speeds at which steam locomotives may be operated without great danger of leaving the track, as a result of the effect of unbalanced reciprocating parts, electric engines are far better able to maintain speed while drawing heavy trains. At speeds of 80 or 90 miles an hour, for example, it is extremely difficult to operate with satisfactory results two steam locomotives at the head of the train; while multiple-unit control places any necessary number of locomotive units absolutely and instantly responsive to the will and touch of a single operator. At high speeds, also, the economy of the steam locomotive falls off rapidly while that of its competitor remains practically constant.

The increase in average speed resulting from the relatively high acceleration obtainable in the use of multiple-unit electric equipment in service where stations are very close together; *e.g.*, elevated and subway lines in cities, and in suburban service in the vicinity of large cities, has been discussed frequently from the theoretical standpoint and is well understood.

3. *General Comfort of Passengers:* The great advantages of electric traction in respect to comfort of passengers are well-known. Cleanliness and improved ventilation made possible by the elimination of smoke and cinders; lighting practically without heat and at low cost by a system which makes it easy to place lights in any desired location, and heating apparatus effectively and conveniently controlled, are factors of very great importance in building up passenger business under conditions of competition. In operating through tunnels, ventilated with difficulty, the electric motor, in eliminating smoke and the gases of combustion, possesses an advantage which is frequently controlling.

4. *Safety:* So much has been said and printed in the daily press regarding the alleged dangers of electric traction, that it is well to place on record here a statement of the considera-

tions which inevitably lead to the conclusion that electric traction, if the equipment be properly designed and installed, is essentially and materially safer, so far as the traveling public is concerned, than steam traction. The more important of these considerations are:

a. The fact that in case of a rear-end collision, which is perhaps the most frequent form of accident experienced in the operation of our railway systems, the energy which propels the electric train can be shut off generally with great promptness. On the other hand, the steam locomotive carrying in its fire-box from 1500 to 2000 lb. of coal heated to incandescence, almost invariably sets fire to any broken cars, or other combustible material with which it comes in contact. Where the electric supply to trains is obtained at low potential from a third rail, the risk of short circuit, which may result in fire if the cars be not fireproof, is greater than it is in the case of overhead construction, even when the voltage employed in the latter case is very high. In fact, in the latter case it may be said that risk from the physiological effects of the current or from fire resulting from short circuit, is practically eliminated, except perhaps in tunnels of very limited clearance.

b. The elimination of the boiler carrying steam at high pressure, also means the removal of an element of risk which in many railroad accidents has destroyed life.

c. The absence of smoke in tunnels, and consequent ability to see signals clearly at all times, constitutes an advantage of the utmost importance for electric operation.

d. Cars drawn by steam locomotives must be heated either by steam from the locomotives, or by some form of stove carried on the individual cars. In the former case, steam from broken steam pipes becomes a serious source of danger in case of accident; in the latter the hot coals from the stove, even in the improved modern types which have greatly reduced the risk formerly encountered, are a source of danger. The substitution of the electric heater affords opportunity not only for ideal control of temperature of the cars but almost absolutely eliminates risk of fire.

e. The elimination of the gas tank and the oil lamp used for lighting in steam traction, and the substitution of electric lighting, also implies a material gain in safety.

f. The danger of derailment in the case of the electric locomotive is far less than in case of the steam locomotive, by reason of the elimination of unbalanced reciprocating parts which tend to lift the steam locomotive from the tracks. The hammer-blow also, in the case of the steam locomotive, is responsible not infrequently in cold weather for broken rails, as a direct result of which many serious accidents have occurred.

g. The electrification of railways where high-speed passenger traffic is involved, affords opportunity for improved methods of protecting trains by signal systems, automatic or other.

h. The ability to cut off power at will from a given section and therefore from trains operating upon that section under certain conditions, which arise not infrequently in railway service, may be availed of to prevent accidents. In steam railway service, when an operator at a tower having allowed a train to pass learns too late that another train is approaching in the opposite direction, he is powerless to avert the impending collision. Where the motive power of these trains, however, is transmitted by electricity, the power supplied to the section might be cut off and probably in time to prevent the catastrophe.

As against the considerations above referred to, all of which tend to make electric operation safer than operation by steam locomotive, the addition to the permanent way equipment of an electric conductor conveying power to trains imposes in the former case a material risk not involved in the latter. If the power be supplied through a third rail, a guard should be used whenever possible to prevent accidental contact with the rail by employes or by others walking upon or crossing the track. Several effective forms of guard are available, of which at least one has been in service upon a convincing scale for five years.

5. *Reliability of Train Service:* Interesting evidence in respect to the relative reliability of steam locomotives, and of electric motors carried upon cars and controlled by the multiple-unit system of train-control, is derived from the official records of the transportation department of the Manhattan Division of the Interborough Rapid Transit system of New York. Upon the elevated lines, steam locomotives were used from the inauguration of the first constituent line of the ultimate system in 1872 until 1902, during which year and a part of the following year, electric equipment was gradually substituted. The locomotives were operated under exceptionally favorable conditions, were not overloaded, were of simple construction, and admirably maintained. The electric equipment that succeeded them is operating trains which average

5.3 cars as against 3.8 cars in the days of steam operation. The average speed is materially higher. The tractive effort during acceleration of a six-car train is 30,000 lb. as against a maximum draw-bar pull of approximately 7,000 lb. exerted by the steam locomotive.

Accurate record is kept of the duration of every delay in the operation of the trains. The results for the months November 1900 to March 1901, when steam was used, and the corresponding months of the years 1905-6 under conditions of electric operation, illustrate in a striking manner the marked gain in reliability of service which has resulted from the adoption of electricity. For the five months of steam operation the aggregate car-mileage was 18,527,773 miles, and the aggregate delay 8258 train minutes. The car-mileage per train-minute delay was 2243.

For the corresponding period of electric operation, 5 years later, the car-mileage was 25,482,081, the aggregate train-minutes' delay 5970 and the car-mileage per train-minute delay was 4268.

It will be noted that the months involved in the above comparison are those in which the difficulties of operation, owing to weather conditions and number of passengers transported are at a maximum. Snow and sleet are among the greatest difficulties to be overcome in the operation of a third-rail system, when, as in the case of the Manhattan, the third rail cannot be effectively protected by reason of limitations in space available on the stucture. In view of these difficulties and of the increase in density of traffic, the results obtained are remarkable

6. *Increased Capacity of Line.* Electric traction as compared with steam traction enables us to develop much greater sustained tractive efforts with given weight on drivers, by reason of more uniform rotative effort. Even where electric locomotives are used, it also eliminates dead weight by abolishing the tender and facilitating construction under which practically the entire weight of the locomotive is carried upon the drivers. Where the locomotive is dispensed with, and the motors mounted directly upon trucks of cars constituting the train, the best results are obtained, the proportion of weight upon wheels driven by motive power being greater than is otherwise practicable. This increase in weight available for adhesion, in conjunction with the characteristics of the electric motor, makes it possible to attain in electric service rates of accelera-

tion altogether impracticable in steam service; consequently trains in passenger service where short headway is desirable can follow each other at shorter intervals than is feasible where steam motive power equipment is employed.

In the operation of freight trains, if it should ever become practicable to distribute electric locomotives throughout the length of the train and operate them by multiple-unit control, trains of length far beyond present limits could be operated. At present, the length of a freight train is limited by the strength of the draft-gear, and steam locomotives cannot advantageously be distributed at intervals throughout a very long train, as no means is available for controlling their effort simultaneously and satisfactorily.

Obviously, a system permitting distribution of the motive power at convenient intervals throughout the train, and simultaneously controlled by the hand of a single engineman, presents possibilities of increasing track capacity which under conditions now existing on many through lines should be of great value.

7. *Frequency of Stops:* The interurban electric line competing with the steam railroad for traffic between two cities possesses great advantage in the collection and distribution of passengers, from the ability of its cars to stop at any street intersection or other convenient point, instead of receiving and discharging passengers at a single railway station in each town. These frequent stops, however, operate to reduce speed materially, and but for the ability of the electric equipment to accelerate rapidly the limitation would be very serious. As speed between terminals is increased, the tendency to reduce the number of stops made to take on or let off passengers is noticeable in the development of many interurban lines.

8. *Convenient Establishment of Feeder Lines:* Frequency of stops for convenient collection and distribution of passengers, and high speed between terminals, being considerations which are essentially opposed, the advantages of a four-track system permitting operation of local or collecting train units on two tracks, and express trains on the other two tracks, are obvious. The great expense of such a system, however, can be borne only where traffic is very heavy.

A natural development which during the last five years has been very rapid, is found in the use of comparatively short electric trolley lines in connection with steam express service for long-distance runs. This method of utilizing the advantages of local electric lines by the companies operating trunk line systems is eminently wise, and in general should be highly advantageous to the properties concerned while increasing materially the facilities offered to the public. It may be pointed out, however, that were the trunk line systems to utilize electricity for through traffic, the extension and systematic improvement of local feeders would be facilitated for a number of reasons, notably:

1. The fact that power developed in large amount, as for the operation of heavy through traffic, is produced at low cost per unit, and would be available at all points along the line for the operation of cars on local feeder lines.
2. The convenient possibility of attaching cars or short trains arriving on local lines to through trains at points of junction. The multiple-unit system of car equipment lends itself admirably to this method of operation.

ILLUSTRATIONS OF PASSENGER BUSINESS DEVELOPED BY INTERURBAN ELECTRIC LINES.

In a very comprehensive paper presented by Mr. J. G. White before the International Engineering Congress at St. Louis in 1904, the following striking illustrations of the advantages of frequent service are given:

"*Cleveland-Oberlin Line.* These cities are 34 miles apart. The competitors for passenger traffic between these cities and intermediate points are the Lake Shore & Michigan Southern Railroad (steam) and the Cleveland, Elyria & Western (electric). In 1895 the total number of passengers carried by the steam railway between these cities and intermediate points was 203,014. This total decreased gradually after the competing electric line was opened to a minimum in 1899 of 71,755, from which it gradually recovered in 1902 to 91,761, but during this same year the electric road carried a total of about 3,000,000.

"*Cleveland-Painesville Line.* These cities are 39 miles apart. The competitors for passenger traffic are the Lake Shore (steam) and the Cleveland-Painesville & Eastern Railway (electric). In 1895 the steam road carried between the terminals and intermediate points 199,292 passengers, but in 1902 it carried only 28,708 passengers, while the electric system carried 1,537,754 passengers.

"*Cleveland-Lorain Line.* These cities are 26 miles apart.

Competitors are the New York, Chicago & St. Louis Railroad (steam) and the Lake Shore (electric). In 1895 the steam road carried 42,526 passengers but in 1902 it carried only 9,795 passengers, the electric road in the same year carrying 3,896,902 passengers."

The Lackawanna & Wyoming Valley Railway Company, operating a double track system between the cities of Scranton and Wilkes-Barre, Pa., carried, during the four months ending October 1906, 1,396,833 passengers. This railway, 18 miles in length, competes with two double-track steam railways having excellent terminals in both cities, and with a third double-track steam railway having an equally good terminal in Scranton, but a less favorably located terminal at the Wilkes-Barre end of the line. The electric railway charges 30 cents for the ride between the two cities and sells round-trip tickets for 50 cents. Except at certain hours, it operates its service upon 10 minutes' headway. At least one of the steam railways, in the endeavor to retain its passenger business, has reduced its rate to 40 cents for the round trip. It has also increased the frequency of its train service. We have been unable to ascertain the number of passengers carried by the competing steam lines during the four months above referred to, but the earning power of frequent electric service is strikingly demonstrated by the fact that this railroad, operating in competition with three double-track steam railways of practically identical length and substantially equal terminal facilities, should be doing a business which represents an income of $5.00 per capita per annum of tributary population, including that of the terminal cities.

ELECTRIFICATION OF TRANSPORTATION SYSTEMS IN MANHATTAN AND THE BRONX—EFFECT UPON TRAFFIC

A study of the transportation statistics of New York City, particularly during the last decade, is not only of great local interest, but is instructive as illustrating the effect of improvement in transit facilities upon gross receipts.

The data graphically summarized in Figs. 1, 2, and 3 have been compiled from official records; those subsequent to June 30, 1883, being obtained from the reports of the State Surveyor and of the Railroad Commission of the State of New York. The effects of improved service are clearly evident from an inspection of these figures.

In Fig. 1, the line marked "All lines" indicates for each year ending June 30, the aggregate paid fares collected by all surface, elevated, and subway lines in the Boroughs of Manhattan and Bronx. It will be noticed that the aggregate paid fares for the year ending June 30, 1894, and also for the following year, were slightly less than for the year ending June 30, 1893, this reduction doubtless being due to the hard times which then prevailed. With this exception, the aggregate of paid fares for all lines shows in each year an increase over the preceding year. Comparing the Manhattan System for the year 1893 with the same system for the year 1899, a decrease of 21% in paid fares is shown. During the same period the paid fares of surface lines, which meanwhile in large degree had adopted electric operation, increased by 43%. That the decrease in

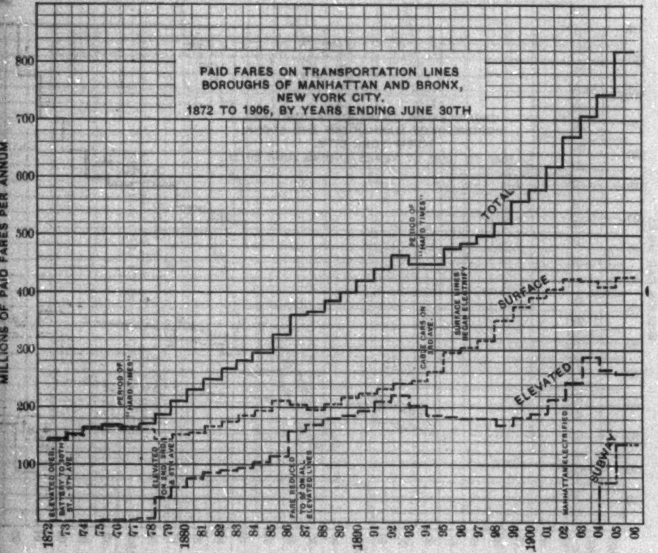

Fig. 1.

business on the elevated lines was not due to any decrease in the service, is shown by Fig. 2, from which it will be seen that the car mileage operated increased steadily during this period. The unavoidable inference is that the diversion of traffic to the surface lines was a direct result of the improved service offered by the latter.

During the year ending June 30, 1901, the last fiscal year of steam operation on the elevated lines, the Manhattan system collected 190,045,741 fares. The surface lines collected 388,103,794 fares. During the year ending June 30, 1904, the Manhattan System, now operated by electricity, collected 286,634,195 fares, an increase of 50%, while the surface lines collected 419,423,092, an increase of about 8%. In the following year, 1904, the subway began operation, and both elevated and surface lines recorded a decrease in fares collected.

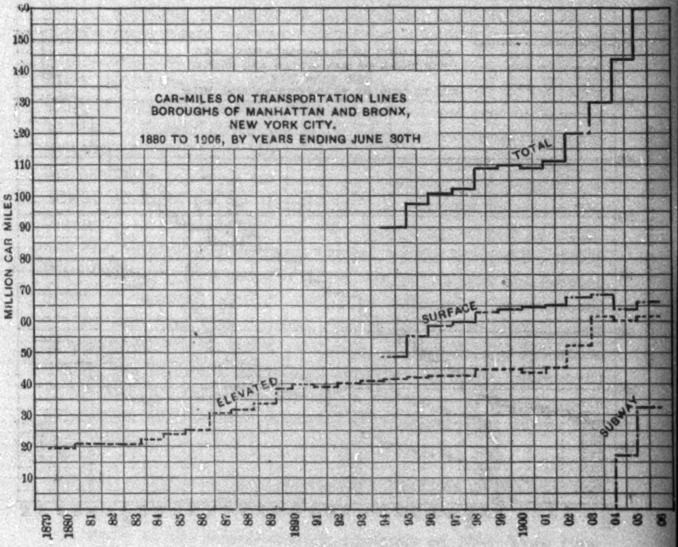

FIG. 2.

In Fig. 4 are plotted curves showing the population of, *a*, Greater New York and, *b*, the Boroughs of Manhattan and the Bronx. The points which fix these curves from 1860 to 1900

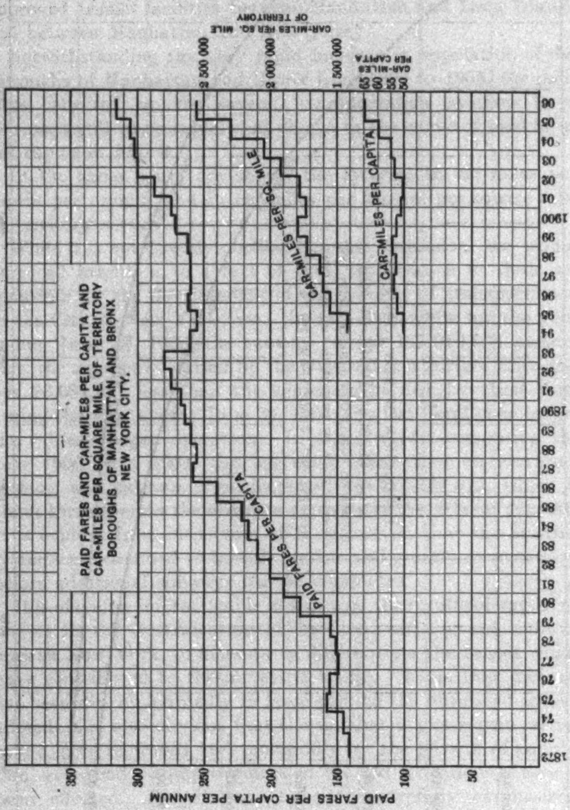

FIG. 3.

inclusive, are from the United States Census Reports. For the years 1910 and 1920 the estimated population is based upon the average rate of change in the per cent. increase per

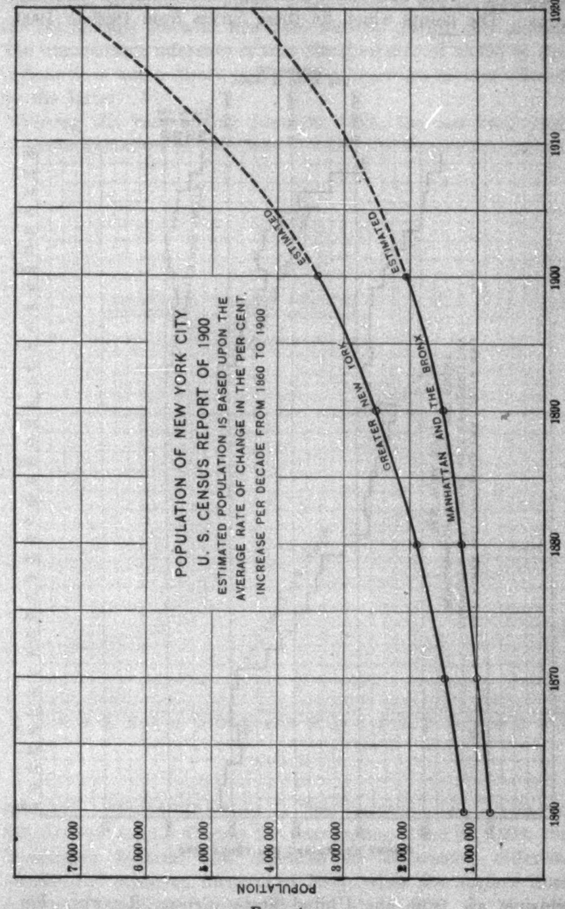
POPULATION OF NEW YORK CITY
U. S. CENSUS REPORT OF 1900
ESTIMATED POPULATION IS BASED UPON THE AVERAGE RATE OF CHANGE IN THE PER CENT. INCREASE PER DECADE FROM 1860 TO 1900
GREATER NEW YORK
MANHATTAN AND THE BRONX
ESTIMATED
ESTIMATED
POPULATION
7 000 000
6 000 000
5 000 000
4 000 000
3 000 000
2 000 000
1 000 000
1860
1870
1880
1890
1900
1910
1920

FIG. 4.

decade from 1860 to 1900. Up to 1905, the population as indicated in these curves is undoubtedly not far from the fact; for 1910 and 1920 the probable populations indicated are interesting, although the curves take no account of the effect of improved transit facilities between Manhattan and Long Island, and between Manhattan and New Jersey.

Notwithstanding the very rapid increase in population of the Boroughs of Manhattan and Bronx from 1890 to 1905, the paid fares collected by the several transportation systems have increased still more rapidly, as shown in the curve of paid fares per capita in Fig. 3.

In the same figure are shown the increase in car-miles per capita per annum, and in car-miles per annum per square mile of territory served.

While it is not directly pertinent to this discussion, we would here call attention to a fact of great importance to those responsible for the development of the systems of transportation in the City of New York; viz., the fact that while for the year ending June 30, 1906, the subway carried 137,919,632 passengers, the aggregate carried by the elevated and surface lines was but 23,684,957 less than the aggregate carried by these lines during the year ending June 30, 1904, the last fiscal year before the subway began operation. In other words, comparing the year 1906 with 1904, the aggregate paid fares on elevated, surface, and subway lines, increased by 114,234,675, which is about three-fourths the ultimate capacity of the present subway. It is evident from inspection of these curves, that the existing systems are destined to be still further and greatly overcrowded before additional subways can be completed.

It is of course impracticable in studying the results of improved service in the electrification of elevated, surface, and subway lines in New York, to attempt to differentiate the causes which have contributed to the increased traffic. While that increase has been due undoubtedly in large part to the improved service offered, it is also obvious that the number of passengers carried would have increased very materially by the growth of population, even had no improvement in the old conditions of service been effected. But it cannot be too strongly emphasized, that while from one point of view improved transit facilities are a result of increased population, from another and equally tenable point of view, increased population is a result of improved transit facilities.

Comparative Costs of Operation.

As the standard with which to compare our estimates of cost of electric operation, we have adopted the grand average results obtained in operation by steam locomotives upon the existing railways of the United States, as set forth in the report of Statistics of Railways for 1904 compiled by the Interstate Commerce Commission, and proof-sheets of the report of the Commission for the year 1905. We shall follow the classification of operating expenses adopted by the commission, and generally used by the railroad companies in their annual reports. The estimated costs of electric operation being approximately determined as compared with the grand averages obtaining in steam railroad practice in this country, the work of determining, for any given case, the relative advantages and disadvantages of steam and electric operation will perhaps be facilitated. We compare, of course, the itemized operating expenses in the case of operation by electricity with corresponding expenses under existing conditions of steam motive power equipment. In estimating operating expenses of electric equipment, we have based conclusions upon results obtained in practice so far as we possess the necessary data.

The substitution of electric for steam equipment involves a large investment in power plant, and in electric conductors and apparatus for conveying power from the power plant to the moving trains, The distributing system for alternating-current equipment, which is the only class of equipment deserving serious consideration in connection with the general problem which we are discussing, comprises an addition to permanent way equipment in the form of overhead construction and electrical conductors conveying power from the power house to the trolley or conductor which is carried above the track. At the present time, the limit of potential generally adopted in this country in constructing alternating-current dynamos is 11,000 volts. Where this voltage is generated, and the distance from the power house to the section of railroad to be electrified does not exceed 25 or 30 miles, step-up and step-down transformers are unnecessary. For greater distances, higher potentials are used upon the feeder circuits between power house and trolley, transformers for increasing the generated potential being installed in the power house, and transformers for lowering the potential to that selected for the trolley; *e.g.*, 11,000 volts, being located in suitable transformer houses at intervals of from 30 to 50 miles, depending chiefly upon density of traffic.

For the trolley, a potential of 11,000 volts is suitable and can be adequately insulated. The mechanical support for the trolley comprises, preferably steel poles with brackets or light steel bridges spanning the track.

The cost of the power plant and distributing system are properly chargeable to capital account.

Our estimates are based upon the assumption that single-phase alternating-current equipment is used; that the trolley potential is 11,000 volts; that each power-house supplies railway line to a distance of 150 miles in each direction, the feeder potential employed being 60,000 volts; that the overhead construction is first class in every respect, steel bridges and steel poles set in concrete being used exclusively for the support of both trolley conductors and feeders.*

As regards equipment of the rolling stock, it is the general practice of our railways to charge against operating expenses all new equipment purchased to replace that which has been worn out in service. In the adoption of electricity, it would seem that this method might be followed in general by our more important railway systems, the substitution of electric equipment beginning naturally upon those parts of the system where the resulting advantages are maximum. In other words, worn-out locomotives, etc., on such a system might be replaced by electric equipment and the cost of the equipment charged against operation, just as the cost of new steam locomotives otherwise required would be charged against operation. For example, the Erie Railroad system, on June 30, 1906, had 1333 locomotives in service. Taking no account of increases necessitated by growth of the company's business, not less than 60 new locomotives should be added to this equipment each year to take the place of those worn out in service. The cost of these new locomotives under steam operation would be charged against " Repairs and renewals of locomotives," and it would seem that their value expended for electric equipment to replace them might be similarly charged. In addition to the purchase of new locomotives to replace those worn out in service, our railroads are compelled from year to year, by the growth of their business, to purchase additional locomotives and other rolling equipment. While these are usually charged against capital account in one form or another, it may be pointed out that any method of financing their cost which may be adopted is equally applicable to electric locomotives.

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*In assuming the use of the single-phase system we are not condemning other systems. The three-phase system has not received from American engineers in general, that degree of consideration which its possibilities and demonstrated advantages justify. Its use, at least on mountain-grade divisions, can be supported by very strong arguments,

In cases where the initial substitution of electricity is on a large scale, as compared with the total rolling stock equipment of the railroad making the change, it is probable that a part if not all of the cost of electric rolling stock equipment will generally be charged to capital account.

We proceed to compare the cost of electric operation with the cost of operation by steam locomotives, using as our standard of comparison the grand average results in steam operation in the United States for the years 1901–1905, inclusive. These average results are set forth in the following tables compiled from the reports of the Interstate Commerce Commission and printed on the three following pages. Many of the items included in this tabulation vary between wide limits in the practice of different railroads.

MAINTENANCE OF WAY AND STRUCTURES

Under the general heading, " Maintenance of Way and Structures," item No. 1, " Repairs of Roadway," if changed at all should show some reduction under conditions of electric operation, but obviously no material change is to be expected. We assume therefore that this item, amounting to 10.818% of total operating expenses, will remain unchanged.

The items, " Renewals of rails," " Renewals of ties," and " Repairs and renewals of bridges and culverts," may be conveniently grouped. In the aggregate, these on the average steam operated railroad amount to 6.33% of the total cost of operation. If the electric locomotive be substituted for the steam locomotive, it is safe to predict that this group of items of expense will be reduced; but it is practically impossible to state with accuracy what the reduction will amount to. In general, it is obvious that the substitution of electric locomotives developing equal draw-bar pull, with axle-loads reduced at least 25% as compared with steam locomotives, and with wheel-bases not exceeding those of steam locomotives, should favorably affect these items. From the best study which we have been able to make of the detailed factors comprised under these three items of the classification, it would seem that under

TABLE I

Item	Amount 1905	Per cent.					Average Five Years	Estimated Cost of operation by Electricity
		1905	1904	1903	1902	1901		
Maintenance of Way and Structures......	274,415,279	19.784	19.519	21.185	22.255	22.272	21.003	22.354
1. Repairs of roadway	144,161,701	10.393	10.348	11.093	11.331	10.294	10.818	10.818
2. Renewals of rails..	18,259,022	1.316	1.298	1.386	1.521	1.676	1.439	5.00
3. Renewals of ties...	36,856,864	2.657	2.519	2.487	2.838	3.140	2.728	
4. Repairs and renewals of bridges and culverts..........	32,166,990	2.319	2.228	2.461	2.593	2.730	2.466	
5. Repairs and renewals of fences, road-crossings, signs and cattle-guards.....	6,179,686	0.446	0.437	0.527	0.625	0.598	0.527	0.527
6. Repairs and renewals of buildings and fixtures..........	29,320,204	2.114	2.147	2.590	2.562	2.417	2.366	1.300
7. Repairs and renewals of docks and wharves..........	2,883,274	0.208	0.209	0.235	0.220	0.283	0.231	0.231
8. Repairs and renewals of telegraph...	2,374,932	0.171	0.179	0.165	0.173	0.158	0.169	0.169
9. Stationery and printing..........	383,158	0.028	0.029	0.032	0.031	0.029	0.030	0.030
10. Other expenses....	1,829,448	0.132	0.125	0.209	0.361	0.317	0.229	0.229
Repairs and renewals of track bonding..............								0.800
Repairs and renewals of overhead construction......								3.250
Maintenance of Equipment..............	288,012,604	20.765	19.967	19.133	19.127	18.629	19.524	12.287
11. Superintendence ..	7,831,965	0.565	0.567	0.559	0.601	0.599	0.578	0.578
12. Repairs and renewals of locomotives.	114,988,428	8.290	7.904	7.408	7.246	6.695	7.509	2.253
13. Repairs and renewals of passenger cars............	27,342,120	1.971	1.951	2.044	2.157	2.277	2.080	2.080
14. Repairs and renewals of freight cars.	113,723,239	8.199	7.777	7.442	7.432	7.436	7.657	6.000
15. Repairs and renewals of work cars.....	3,360,390	0.242	0.231	0.242	0.245	0.233	0.238	0.238
16. Repairs and renewals of marine equipment............	2,650,543	0.191	0.154	0.177	0.215	0.234	0.194	0.194
17. Repairs and renewals of shop machinery and tools.....	9,186,101	0.663	0.704	0.696	0.643	0.605	0.662	0.500
18. Stationery and printing..........	595,571	0.043	0.042	0.046	0.044	0.043	0.044	0.044
19. Other expenses....	8,334,240	0.601	0.637	0.519	0.544	0.507	0.562	0.400

NOTE.—It is customary with some railroads using electric equipment to include under the general heading " Maintenance of Equipment." the maintenance of the power plant and electric transmission systems. Both of these, however, are more conveniently treated by including them in the cost of electric power delivered to the overhead trolley system or third rail.

TABLE I.—*Continued.*

Item	Amount 1905	Per cent.					Average Five Years	Estimated Cost of operation by Electricity
		1905	1904	1903	1902	1901		
Conducting Transportation	769,613,017	55.486	56.670	55.893	54.671	54.979	55.540	43.603
20. Superintendence	25,007,322	1.803	1.779	1.742	1.711	1.726	1.752	1.752
21. Engine-and round-house men	130,437,844	9.404	9.550	9.562	9.401	9.340	9.451	4.710
22. Fuel for locomotives	156,429,245	11.278	12.128	11.675	10.776	10.602	11.292	5.702
23. Water supply for locomotives	9,147,590	0.660	0.659	0.614	0.623	0.612	0.634	0.000
24. Oil, tallow, and waste for locomotives	5,442,970	0.392	0.397	0.389	0.366	0.361	0.381	0.250
25. Other supplies for locomotives	3,295,384	0.238	0.248	0.232	0.218	0.206	0.228	0.228
26. Train service	90,654,520	6.536	6.735	6.677	6.737	7.011	6.739	6.739
27. Train supplies and expenses	21,963,086	1.583	1.581	1.552	1.500	1.471	1.537	1.000
28 Switchmen, flagmen and watchmen	60,141,422	4.336	4.386	4.313	3.984	3.848	4.173	4.173
29. Telegraph expenses	24,823,266	1.790	1.788	1.754	1.784	1.785	1.780	2.000
30. Station service	89,304,658	6.438	6.605	6.664	6.832	6.947	6.697	6.697
31. Station supplies	8,961,573	0.646	0.686	0.667	0.676	0.672	0.669	0.669
32. Switching charges, balance	4,201,050	0.303	0.280	0.244	0.272	0.319	0.284	0.284
33 .Car per diem and mileage, balance	18,835,325	1.358	1.358	1.400	1.480	1.618	1.423	1.423
34. Hire of equipment, balance	3,040,641	0.219	0.195	0.214	0.180	0.161	0.194	0.194
35. Loss and damage	19,782,692	1.426	1.279	1.094	0.990	0.819	1.112	0.750
36. Injuries to persons	16,034,727	1.156	1.196	1.120	1.048	0.911	1.086	1.000
37. Clearing wrecks	3,594,658	0.259	0.275	0.284	0.221	0.189	0.246	0.200
38. Operating marine equipment	9,903,479	0.714	0.696	0.745	0.721	0.862	0.748	0.748
39. Advertising	5,959,380	0.430	0.418	0.428	0.429	0.428	0.427	0.427
40. Outside agencies	19,688,261	1.419	1.411	1.449	1.579	1.615	1.495	1.495
41. Commissions	233,987	0.017	0.022	0.044	0.077	0.089	0.050	0.050
42. Stock yards and elevators	786,850	0.057	0.060	0.057	0.069	0.075	0.064	0.064
43. Rents of tracks, yards and terminals	23.947,881	1.727	1.563	1.544	1.519	1.724	1.615	1.615
44. Rents of building and other property	4,814,407	0.347	0.382	0.411	0.440	0.440	0.404	0.404
45. Stationery and printing	8.772,789	0.632	0.640	0.642	0.622	0.638	0.634	0.634
46. Other expenses	4.408,010	0.318	0.353	0.376	0.416	0.510	0.395	0.395

TABLE I.—*Continued.*

Item	Amount 1905	Per cent.					Average Five Years	Estimated Cost of operation by Electricity
		1905	1904	1903	1902	1901		
General Expenses.....	55,022,127	3.965	3.844	3.789	3.947	4.120	3.933	3.933
47. Salaries of general officers...........	11,676,616	0.842	0.841	0.823	0.925	0.984	0.883	0.883
48. Salaries of clerks and attendants...	18,582,142	1.340	1.313	1.254	1.244	1.262	1.283	1.283
49. General office expenses and supplies..............	3,459,470	0.249	0.230	0.234	0.249	0.257	0.244	0.244
50. Insurance.........	6,885,932	0.496	0.471	0.432	0.412	0.384	0.439	0.439
51. Law expenses.....	7,096,275	0.512	0.513	0.541	0.558	0.549	0.549	0.549
52. Stationery and printing (general expenses)........	2,439,781	0.176	0.170	0.175	0.168	0.161	0.170	0.170
53. Other expenses....	4,861,911	0.350	0.306	0.3330	0.391	0.447	0.365	0.365
Recapitulation of Expenses...........								
54. Maintenance of way and structures	274,415,279	19.784	19.519	21.185	22.255	22.272	21.003	22.354
55. Maintenance of equipment........	288,012,604	20.765	19.967	19.133	19.127	18.629	19.524	12.287
56. Conducting transportation.........	769,613,017	55.486	56.670	55.893	54.671	54.979	55.540	43.603
57. General expenses..	55,002,127	3.965	3.844	3.789	3.947	4.120	3.933	3.933
Grand Total......	1,387,043,0	27100.	100.	100.	100.	100.	100.	82.177

electric operation they should be reduced about one-fourth; in other words, they should approximate 5% of the total operating expenses. It is not to be imagined, of course, that railroads adopting electric traction would limit themselves to equal draw-bar pull and not increase loads. They would, naturally, take advantage of the possibility of increasing draw-bar pull so far as strength of draft-gear may permit, thereby effecting gains far outweighing the decrease in operating expenses represented by saving in maintenance of roadway, rails, and ties, which would result from a decrease in the weight of locomotives. This argument is valid, not only with reference to high-speed passenger traffic, in which the hammer-blow of the engine is emphasized, but also in connection with freight traffic, where in recent years there is a marked tendency to employ trains of great length and locomotives of extreme weight.

The cost of track-maintenance is increased by reason of the electric bonding of the rails. This bonding, including the cost of special bonds necessary where an automatic track signal system is used, will cost about $500 per mile under average conditions. Its cost of inspection and maintenance should not exceed $50 per mile of single track per annum.

The annual cost of " Renewals of rails," " Renewals of ties," and " Repairs and Renewals of bridges and culverts," averages in the United States $400 per mile of track, which as above stated, is 6.633% of average operating expenses, under steam operation, and for equal trains, as we have estimated, 5% for electric operation. The effect of the cost of track-bonding, therefore, would increase the items under consideration by about one-eighth, which is equivalent to an increase of 0.8% in operating expenses. To avoid possible confusion, we include the cost of " Repairs and renewals of track bonding " as a separate item in the column " Estimated Cost of Operation by Electricity."

Under the general conditions which will govern where electricity is substituted for steam in railway operation, there can be no doubt that the substitution will result in a material reduction in the cost of maintenance of rails, ties, bridges, and culverts. In this substitution electric locomotives will be used for freight traffic, while for passenger traffic locomotives will be eliminated ultimately and multiple-unit car equipments employed. For the immediate future, however, locomotives will be employed not only for freight traffic but also in some cases for passenger traffic, for the practical reasons which have impelled the Pennsylvania, the New York Central, and the New York, New Haven & Hartford systems in electrifying their New York terminals to adopt electric locomotives for handling their through trains.

The hammer-blow upon rails, is largely and in some cases wholly avoided by the adoption of electricity; *e.g.*, the entire electric equipment of the heavy locomotives used in the Baltimore tunnel is spring-borne; this is true also of the 70-ton Ganz locomotives recently placed in operation upon the Valtellina, and of the single-phase locomotives ordered by the New York, New Haven & Hartford Railroad. In the case of the locomotives recently constructed for the New York Central Railroad the motor armature is carried by the axle. The armature and axle weigh 7460 lb.; obviously the hammer-blow, even in this case, is not to be compared with the tremendous blow due to unbalanced reciprocating parts, the inertia of which in steam locomotives at high speeds is sufficient actually to lift the wheels from the track.

The hammer-blow is less serious at the speeds at which freight trains usually travel; but even if we ignore entirely the effect of the unbalanced parts in this case, the electric locomotive still possesses the important advantage that its ratio of tractive effort to weight is much higher than that of the steam locomotive.

The most striking feature in American railway operation in recent years is the increase in length of train and weight of locomotive, under pressure of business which has increased at a ratio much exceeding the ratio of increase in track mileage. Despite the efforts of our railway engineers and managers, the roadbed has not kept pace with this advance; and while the weight of rail has been increased materially, the factors of safety as regards weight upon ties and bridges, and particularly as regards the security of rails against displacement due to side-thrust on curves, are by no means what they should be, and yet apparently have reached their limit. Lieut.-Col. Yorke, Chief Inspector for the British Board of Trade, in his report of the results of his observations in the United States in 1903, called particular attention to this fact, and expressed the opinion that American railway practice is tending towards British practice in respect to the distribution of weight on ties secured by inserting chairs between the rails and the ties.

In view of the fact that our railways have been spending large sums of money to increase the stability of the roadbed, to strengthen bridges and culverts, and to maintain rails in position upon the ties, the advantage which the electric locomotive possesses in its higher ratio of tractive effort to weight is important, even in freight traffic at low speed. The necessity of utilizing track capacity to the utmost, and the economies resulting from the operation of long trains, have resulted in gradually increasing the length and weight of freight trains until it would appear that the limit has been reached, unless further improvement in draft-gear, track, and roadbed, and further increase in weight of locomotives, be found possible. It is evident, however, that if electric locomotives operated by the multiple-unit system could be used and located at suitable distances throughout the train, the possible length of a freight train would not be limited by its practicable motive power equipment.

Operation of electric locomotives thus located presupposes upon all roads the addition of control-wiring and couplers to freight cars. The report of the Interstate Commerce Commission for 1904 shows that of a grand total of 1,845,304 locomotives and cars operated by our railways, 1,823,030 are equipped with automatic couplers and 1,554,772 are fitted with train brakes. At the present time, the cost of train-line and couplers would approximate $75 a car, but a reasonable cost for the apparatus required, if furnished in large quantities, would not exceed $50 per car.

As regards the making up of trains, it is now necessary to couple the air-line between cars, and the additional labor of connecting the control-couplers would not be serious.

While the cost of equipping freight cars, and of additional labor involved in connecting trains, is very small as compared with the immense advantages which in many cases would result from the ability to distribute locomotives at suitable intervals in a freight train, and control them simultaneously and perfectly by the hand of the engineman at the head of the train, the probability of adoption of multiple-unit operation for freight trains appears remote, since there is apparently no sufficient reason why a railroad company not adopting electricity should equip its cars for electric operation over the lines of another company which may adopt the newer motive power. Whether it be possible for a company desiring to avail itself fully of the advantages of electric traction for freight, as well as for passenger traffic, to bring to bear upon other lines interchanging freight with it, pressure sufficient to induce those lines to spend $50 per freight car for electric equipment is a question outside the scope of our present consideration.

Reverting to Table I, item 5, "Repairs and renewals of fences, road-crossings, signs and cattle-guards," will not be changed by the adoption of electricity.

Item 6, "Repairs and renewals of buildings and fixtures," includes repairs and renewals of engine houses and shops, also water tanks and coal-handling apparatus. Under electric operation, it is evident that this item would be materially reduced. This subject will be further discussed when we come to consider item 12, "Repairs and renewals of locomotives." It is conservative to say that for the operation of a given train-mileage, under the average conditions of railway service in this country, the number of electric locomotives required should not exceed one half the number of steam locomotives now used. The reduction in the number of locomotives implies, of course, a reduction in the cost of repairs and renewals of engine house and shops, and taking this into account, in connection with the elimination of water tanks and coal-handling apparatus, distributed along the line, it is our opinion that this item will be reduced from 2.366% to about 1.3% of the total annual operating expenses.

Item 7, " Repairs and renewals of docks and wharves " obviously will not be affected.

Item 8, " Repairs and renewals of telegraph." It is probable that this item will be somewhat increased in general where electric operation is adopted. The effect upon the operating expenses, however, is so slight as to be practically negligible in our consideration of the general problems of comparative expenses of steam and electric service.

Item 9, " Stationery and printing " will not be changed.

Item 10, " Other expenses " we may assume will not be affected.

Under the general heading " Maintenance of Way and Structures," the classified statement of operating expenses of a railroad electrically equipped includes the following items in addition to the foregoing:

a. " Repairs and renewals of track bonding."

This has been referred to in our discussion of items 2, 3, and 4, and it is included in our tabulated statement as a separate item amounting to 0.8% of operating expenses.

b. " Repairs and renewals of overhead or third-rail construction."

From detailed calculations of the cost of high class overhead construction, where two tracks are to be equipped the cost of overhead construction is approximately $10,300 per mile. This includes trolley conductors equivalent to No. 4/0 wire B. & S. gauge, insulated for 11,000 volts alternating, and supported by steel cables, carried by substantial steel bridges set in concrete, and spanning the tracks. For single-track work using steel poles and brackets and catenery support, the cost closely approximates $4800 a mile.

Of the total line mileage of the United States in 1905, amounting to 216,974 miles, approximately 0.4 are in double track, including yards and sidings for single-track lines, and 0.6 are single-track.

The grand average cost of overhead steel construction of the type considered, therefore, closely approximates $5000 per mile of track. In this case, our estimate of the annual cost of " Repairs and renewals of overhead construction " cannot rest directly upon actual experience, since practically no overhead construction of this character is in use under the conditions of railway service. We may, however, base conclusions which should be reasonably correct upon consideration of first-class overhead trolley construction such as is used by our best interurban lines. Some light is also thrown upon the subject by extensive experience in the operation of high potential transmission circuits, and the experience of the Valtellina line is particularly instructive.

Light steel bridges, set in concrete, subject to the comparatively slight strains involved in supporting the light conductors required, should last almost indefinitely if kept properly painted. The absence of smoke and gasses from locomotives favors their long life. The cost of these steel bridges and poles is a large part of the overhead construction.

The wear of the trolley wire will depend upon density of traffic, but its original cost is only $700 a mile, and judging from the experience of ordinary trolley lines and the results obtained on the Valtellina its life should be long.

The steel catenary cables supporting the conductor being well galvanized should last many years without renewals.

Breakage of insulators, such as are now available, will not constitute a large item of expense.

As regards life of steel structures, it is instructive to note the fact that much of the structure of the Manhattan Elevated lines still in use is more than 30 years of age, and is apparently unimpaired notwithstanding the heavy and frequent traffic which it has carried and still carries.

It is probable that engineering opinion in regard to the amount which should be allowed for " Repairs and renewals of overhead construction " under consideration will not be unanimous, but taking into account all of the factors which appear to affect the problem, it is our judgment that the amount required should not exceed $150 per mile of track per annum. This is equivalent to $210 per mile of line per annum, the average ratio of track-mileage to line-mileage being 1.4 to 1.

The increase in operating expenses due to this item is about 3.25% the average operating expenses per line-mile in the United States for the year 1905 being $6451.00.

It is of course, possible to erect a much cheaper form of construction if wood poles be used. Though the first cost of such construction is low, it involves repairs and renewals constituting a much larger percentage of its cost than in the case of the steel bridge and pole construction set in concrete. The annual effect upon operating expenses with this type of construction as an average figure may be expected to approximate 2.5%.

"MAINTENANCE OF EQUIPMENT."

Item 11. "Cost of superintendence" will not be changed.

Item 12. "Repairs and renewals of locomotives" amounts to 7.509% of the average operating expenses of our steam railroads. This item, as we find in the classification of operating expenses prescribed by the interstate Commerce Commission, "does not include the expense of cleaning boiler tubes and packing cylinders, nor ordinary regular inspection, this being charged to the item "Engine and Roundhouse Men." It does include "all expenditures for account of repairs and renewals and rebuilding of locomotives, tenders, snow-plows (when attached to locomotives), furniture and loose and movable tools and supplies used in connection therewith. It also includes the cost of locomotives, tenders and appurtenances thereunto belonging, built or purchased to make good the original number charged to construction or equipment."

As regards "Repairs and renewals of electric locomotives," actual experience to date is not sufficient to justify us in fixing a figure for this item which can be regarded as established. There is, however, evidence sufficient to justify an estimate which in the average case should be approximately correct.

Before considering data based upon experience, it is pertinent to remark that a moment's consideration of the constituent details of mechanism, their relative complexity, and their respective functions, leads directly to the conclusion that the repairs and renewals of an electric locomotive should be very small as compared with the same item of expense in the operation of a steam locomotive. If we imagine for a moment that electric locomotives had been in use for many years while steam locomotives had but recently come forward as competitors, and that the engineering world of to-day being familiar for years with the essential simplicity of the electric motor as applied to traction purposes, were now called upon to judge the comparative merits of the essentially complicated aggregation of mechanism which we call a steam locomotive, the verdict, as regards the relative cost of repairs and renewals to be expected, is obvious but the argument *a priori* cannot be conceded, and we proceed to consider such evidence based upon comparative results in actual service as we have been able to secure.

1. INTERBOROUGH RAPID TRANSIT CO., MANHATTAN DIVISION.

In the operation of the Manhattan Railway under steam and electric traction, respectively, data for interesting comparisons are afforded; although owing to the fact that in this case multiple-unit electric equipment, applied to two-thirds of the cars constituting the trains, has been substituted for the steam locomotive, the comparison is less favorable to electric operation so far as this item of expense is concerned than it would be were electric locomotives used. The reason is found in the relatively great complication of multiple-unit equipment as compared with locomotive equipment; as a result of this the number of parts in this case is multiplied in the approximate proportion of three to one, and the cost of repairs and renewals is therefore radically increased beyond what it would be were electric locomotives employed.

For the year ending June 30, 1901, the car-mileage operated by the Manhattan Railway was 43,860,158. The cost of repairs of locomotives was $173,609, or 0.39 cents per car-mile.

For the year ending June 30, 1906, the car-mileage operated by the Manhattan Railway was 61,723,112. The cost of repairs of the electric equipment, including lamps, lamp wiring, and heaters, was $171,927, or 0.28 cents per car-mile.

Had electric locomotives been used instead of the multiple-unit system, the number of parts constituting the electric equipment, as stated, would have been about one-third that now in use. These parts would have been larger and more expensive than the corresponding individual parts constituting the multiple-unit equipment, but the cost of repairs of the aggregate electrical equipment (which is largely labor of inspection) probably would not exceed 60% of the present cost. The results are further influenced unfavorably to electric traction as regards this comparison by the fact that the speed, and consequently the power consumption per car, have been radically increased, and by the fact that the repairs and renewals of lamps, heaters, and wiring are included.

A careful consideration of the detailed factors involved has led us to the conclusion that had electric locomotives been substituted for steam locomotives, and had the weight and speed of trains not been increased, the cost of repairs of electric equipment would have approximated 0.2 cents per locomotive mile. We estimate also that the cost of repairs to these small locomotives exclusive of their electric equipment operating under the existing conditions would not have exceeded 0.2 cents per locomotive-mile, and that the total cost would have approximated one-fourth of the cost of the corresponding item under steam traction. This figure of course is available only as a ratio in our consideration of the general railway problem.

The very low cost which was actually obtained in the case of steam locomotives on the Manhattan; viz., 1.57 cents per locomotive mile, is explained by the extremely simple construction of the engines, the fact that they were not overloaded, were operated on an elevated structure, and were admirably maintained. It is also to be noted that the amount expended for repairs was minimized in view of the contemplated adoption of electricity.*

In applying to the general railroad problem evidence afforded by Manhattan experience, it must be noted that the elevation of the tracks places the motors beyond the reach of the dust or cinders which the rush of a train at certain seasons raises from the average railway track. On the other hand, the fact that the average run between stations on the elevated system is only about 2000 ft. exposes both motor and control to the action of brake-shoe dust which is liberated in quantities many times as great as would be the case in average railway service, and this brake-shoe dust is far more injurious to both motors and control than is dust from disintegrated ballast or cinders.

In designing electric equipment for general railway service, it is advisable and not difficult to protect the motors effectively against the admission of dust of all kinds, particularly in cases where locomotives rather than multiple-unit equipment is adopted. This would be accomplished naturally by thoroughly enclosing the motor, and ventilating it by forced draft so directed as to prevent admission of dust.

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*In this connection it is interesting to note that the cost of maintenance of locomotive and average train under steam operation for the year ending June 30, 1901, was 4.2c. per train-mile while the cost in the case of an equivalent electric train, as shown by records for corresponding months for the year ending June 30, 1906, was 2.1c. per train-mile.

2. INTERBOROUGH RAPID TRANSIT COMPANY, SUBWAY DIVISION

For the year ending June 30, 1906, the car-mileage operated by the New York Subway was 31,931,073. The cost of repairs and renewals of electric equipment of rolling stock was 0.38 cents per car-mile. Estimating the probable cost of repairs and renewals of electric equipment, were electric locomotives in use instead of the multiple-unit car equipment, the approximate cost in this case works out at 0.7 cents per train-mile. A locomotive doing the same work as the electric equipment of the average train in the subway (about five cars) must be capable of exerting a draw-bar pull of 30,000 lb., which with 20% adhesion calls for 75 net tons on drivers. This is about double the weight on drivers of the average steam passenger locomotive, and the figure 0.7 cents per train-mile, obtained in actual service under conditions very severe in respect to maintenance of electric equipment, by reason of the presence of great quantities of brake-shoe dust, is to be compared with the cost of maintenance of steam locomotives exclusive of running-gear, frame, cab, and those other parts common to both electric and steam equipment.

3. WILKES-BARRE & HAZLETON R.R.

Operation for the year 1905:

Equipment comprises motor cars weighing 43 tons without passengers, and equipped with four 125-h.p. motors and multiple-unit control.

Effective draw-bar pull (20% adhesion) = 17,000 lb.

Speed of operation in local service = 30 miles per hour.

Total length of run = 27 miles.

Average number of stops = 6.

Car-mileage operated in 1905 = 262,947.

Cost of repairs and renewals of electric motors = $1,021.70 = 0.39 cents per car-mile.

This road operates in a mountainous country, ranging in elevation from about 500 ft. to 1700 ft. above sea-level. About one-third of the length of the road is on a grade of 3%.

4. LACKAWANNA & WYOMING VALLEY RAILROAD.

Operation for a period of four months ending October 31, 1906:

Equipment: *a*, 16 passenger cars, 77,500 lb. each; *b*, 14 passenger cars, 64,500 lb. each; *c*, 4 freight and express motor cars, 61,300 lb. each; *d*, 1 electric locomotive, 94,600 lb.

Car-mileage operated = 527,554.

Repairs and renewals of electric equipment = $4,450.43 = 0.84 cents per car-mile.

5. NIAGARA, BUFFALO & LOCKPORT RAILROAD.

Operation for a period of six months ending Nov. 30, 1906:

Equipment: passenger cars weighing about 60,000 lb., driven by four direct-current motors.

Average speed outside of Buffalo city limits, 20 miles an hour. Approximate number of stops one way trip: 30 on Buffalo & Niagara Falls division, and 6 on Buffalo & Lockport division.

Length of run outside of Buffalo, approximately 20 miles.

Car-mileage operated, 1,309,682.

Repairs and renewals of electric equipment, 0.79 cents per car-mile.

6. RETE ADRIATICA-VALTELLINA LINE.

Perhaps the best instance of electric operation directly comparable with cost of steam operation is afforded by the records of the actual results realized on the Valtellina line where both freight and passenger traffic are operated over a line 66 miles in length, traversing a very rugged country and in the winter exposed to severe climatic conditions. The equipment for the year ending July 1, 1904, comprised 10 motor cars and five 70-ton locomotives. The service performed amounted to 61,934,569 ton-kilometers. The average annual mileage of motor cars and locomotives amounted to 54,351 kilometers, while the steam locomotives superseded by electric equipment never exceeded an average of 29,000 kilometers.

The total cost of electrical and mechanical repairs to locomotives and motor cars, for the year ending July 1904, works out at 1.4 cents per locomotive or motor car-mile. During the last six months of 1906, the repairs to locomotives cost 1.8 cent per locomotive-mile. The rolling stock used on this line is excellent in design and construction and is particularly well adapted to operate in railway service at low cost of maintenance, by reason of the fact that three-phase motors and water rheostats are employed instead of commutating motors and switch-control. The equipment has not been operating long enough to have reached the point where renewals, as distinguished from repairs, have become necessary.

Summarizing the foregoing we have the following:

	Tractive effort 20% adhesion	Repairs of electric equipment of equivalent electric locomotive. Estimated
Manhattan Railway..........	22,000 lb	0.5¢
Subway train..............	33,000 "	0.7¢
Wilkes-Barre & Hazleton R.R.	17,000 "	0.38¢ (actual)
Lackawanna & Wyoming Valley R.R..................	14,000 "	0.84¢
Niagara, Buffalo & Lockport R.R....................	12,000 "	0.79¢
Rete Adriatica-Valtellina line Locomotives, complete cost of maintenance...........		1.8¢ (actual)

It may be conceded freely in respect to the foregoing data that they are neither sufficiently comprehensive in scope nor extended in respect to duration of service to justify definite and final conclusions. It must be noted also on the one hand that the cost of maintenance may be expected to decrease by reason of further improvement in the construction of apparatus of comparatively new types, and on the other hand that the costs given are for inspection and repairs rather than renewals, since the time has not arrived when any of this equipment has been thrown aside and replaced by new equipment charged to this item of operating expenses as is usual with steam railways.

The reports of the Interstate Commerce Commission do not show what proportion of the item, "Repairs and renewals of locomotives" is chargeable to renewals, but from inspection of detailed reports of our most important railway systems it seems fair to assume that in the case of the average railway from 4% to 5% of the total cost of repairs and renewals of locomotives represents the cost of renewals.

Taking into account all of the various considerations which must affect the conclusions in the general case, so far as we have been able to gather them, we are of the opinion that for equal draw-bar pull, the repairs and renewals of electric equipment of locomotives, assuming good design and construction according to present standards of the art, should not exceed 1 cent per locomotive-mile, and will probably approximate 0.9 cent per locomotive-mile.

Taking the higher figure, it is evident that the substitution of electric equipment for all parts of a steam locomotive other than frame, wheels, axles, cab, and other parts which are common both to electric and steam locomotive construction, a very great saving is effected. We have been unable to fix with satisfactory exactness a figure representing the average cost of repairs and renewals of these parts, but it would seem liberal to allow 1.5 cents per locomotive-mile, this being equivalent to an allowance of something over $400 per annum per locomotive. Taking this figure and adding the estimated costs of repairs and renewals of electric equipment, we have 2.5 cents per locomotive-mile as the estimated total cost of repairs and renewals of electric locomotives, performing the average work now done by steam locomotives.

In 1904 the aggregate revenue train-mileage operated was about 1,050,000,000. To cover locomotive mileage in switching, operating work-trains, and pushers we assume 1,300,000 locomotive-miles. In 1904 the aggregate repairs and renewals of locomotives was $105,633,752, the average cost per locomotive-mile, therefore, being 8.1 cents. A reduction to 2.5 cents, therefore, is equivalent to a saving of 70% in the cost of this item, or 5.256% of operating expenses, reducing this item to 2.253% of total operating expenses under electric operation.

In the foregoing consideration of the item repairs and renewals of locomotives, we have assumed equal locomotive mileage per day in steam and electric service. The item of expense under consideration will be proportional approximately to the mileage, and therefore we have made the comparison upon this basis.

The relative number of locomotives required for a given service is, however, a question of much importance and may here be appropriately referred to.

According to the report of the Interstate Commerce Commission for 1904, the aggregate train-mileage operated in the United States as above stated was 1,050,000,000. The locomotives in service numbered 46,743. The effective train-mileage, not including work-trains, pushers, or shifting mileage, was 58 miles per locomotive per day. We have been unable to ascertain from the report of the Commission what percentage should be added to this figure to cover accurately the locomotive mileage of work-trains and shifting and to take account of double headers and pushers, but inspection of the report of a number of our leading railways indicates that the effective train mileage averages from 70% to 75% of the locomotive mileage. It follows, therefore, that the daily run of the average locomotive in the United States is approximately 80 miles. Naturally there is a wide variation in the performance of locomotives on various lines; *e.g.*, passenger mileage as shown by reports of some of our leading railways varies from 90 miles to nearly 200 miles a day and individual cases are reported of locomotives making as much as 300 miles a day.

The average freight locomotive is actually on the road not more than 6 hours in each 24-hour period, and the same figure is approximately correct for the average passenger locomotive. In the case of electric locomotives there is no reason, so far as the mechanism is concerned, why it cannot be kept in practically continuous service. Ordinary inspection and maintenance require very little time, and if the equipment be well designed and constructed repairs of magnitude will be necessary only at intervals very infrequent as compared with steam practice.

The fact that the average daily run of the average locomotive is approximately 80 miles, is due in large measure to causes which would still exist were electric locomotives substituted. The time spent by freight locomotives in yards and terminals making up trains or awaiting opportunity to take their place in the processions of trains which in these days are demonstrating the insufficiency of track equipment for the business of the country, is a large factor. Perhaps this would not be greatly modified were electric locomotives employed. But other considerations which operate to reduce average mileage are the facts that the steam locomotive spends a large part of its life in the repair shop, and a still larger part in firing up and preparing for its work and in withdrawing fires, having boiler tubes cleaned, etc., after its daily run. Nothing short of years of actual experience can establish definitely the ratio of electric to steam locomotives required in average service, but it seems reasonable to assume that this ratio will not exceed 2 to 3 and will probably approximate 1 to 2. It will be noted that the foregoing estimate of cost of repairs and renewals is independent of any assumption as to the relative number of locomotives required since it is reckoned on locomotive mileage.

Item 13. "Repairs and renewals of passenger cars." In cases where electric locomotives are substituted for steam locomotives, there should be some reduction in this item. Painting should be considerably reduced by reason of the elimination of smoke. The life of the upholstery and interior decoration of the car will be increased.

Item 14. "Repairs and renewals of freight cars." This item will be favorably and very materially affected if it should ever prove practicable to operate heavy freight trains by locomotives located at intervals throughout the trains and controlled by the multiple-unit system. As has been pointed out, however, this will become practicable only when a large proportion of the freight cars in use are supplied with electric train line equipment. The bare possibility of this at present may seem fanciful, but those who realize the extent to which the wear and tear of freight cars results from the terrific strains to which the draft-gear is subjected under present operating conditions, especially on mountain grades, and who understand also the increase in track capacity and decrease in cost of train crews which would result from the adoption of a system which makes it possible, if necessary, to double the length and weight of the longest and heaviest freight trains now in use, will be ready to give this possibility serious consideration. The mere substitution of electricity for steam without altering the present make-up of trains, so far as location of the locomotive is concerned, makes it possible to operate two or more locomotive units at the head of the train, and to utilize their power to the utmost by multiple-unit control operated by a single operator on the leading engine.

Assuming that the methods of train operation remain the same, the adoption of electricity will still effect a reduction in the cost of Item 14, and for two reasons, viz.;

1. The practical elimination of damage by fire which now frequently is superimposed upon damage caused by collision or derailment.

2. Reduction of wear and tear of wheels and brake equipment in descending long grades, by reason of the opportunity afforded to brake the trains by causing the motors to operate as generators. On lines where grades are heavy and of considerable length, the saving thus effected will be large. Generally speaking, the energy developed by the motors working as generators will be returned to the overhead circuit and utilized in coöperation with energy from the power house to furnish power to trains on the same division which may be ascending the grade.

No statistical data are available upon which to base an estimate of the probable reduction in this item to be expected from this cause. On comparatively level lines it will not be important, but on mountain-grade divisions it should operate to prevent a very large proportion not only of wear and tear directly due to grade but also of the destructive freight wrecks which are now so frequent. In the way of an estimate, nothing more definite than a guess based upon consideration of probabilities, and the views of various operating officials, can be advanced; but in the opinion of the writers the general substitution of electricity for steam operation in freight service should reduce this item from 7.657% to something like 6% of operating expenses.

Item 15. " Repairs and renewals of work cars," will not be changed materially.

Item 16. " Repairs and renewals of marine equipment," obviously will not be changed.

Item 17. " Repairs and renewals of shop machinery and tools," will be reduced under electric operation since the repairs to locomotives will be decreased radically as shown, and since the tool equipment required for the electrical machinery is materially less expensive and varied.

It would seem reasonable to expect that this item would be reduced from 0.662% to about 0.5% of total operating expenses. Of course a large proportion of the shop machinery and tools are for car repairs.

Item 18. " Stationery and printing," will not be changed.

Item 19. " Other expenses." The classification of operating expenses includes under this item " all expenditures for account of electric light, torches and lamps used in machinery department, shops, roundhouses and offices and the oil and material for the same; the proportion of labor and material for the proper operation and repair of electric lights used in connection with other departments; wages of engineers and firemen and the cost of fuel and water in operation of stationary engines or boilers for supplying power and heat to shops, buildings and roundhouses."

Other factors comprised are comparatively small and it is evident that the ability to use electricity for light and power purposes in shops, roundhouses and offices produced at a works cost of 0.6 cents and delivered to the point of consumption at a figure which on the average will approximate 0.75 cents will effect a material reduction in this item. We estimate that it will be reduced to about 0.4 cents.

CONDUCTING TRANSPORTATION.

Item 20. "Superintendence," will not be changed.

Item 21. "Engine and roundhouse men," includes in addition to the engine crew, round-house men whose work, of course, is chiefly in connection with the cleaning and maintenance of the engines. This item averages for the railroads of the United States 9.451% of the operating expenses, of which 91%, or about 8.6% of the operating expenses are for engine men and for firemen. Of this 8.6% approximately 5.5% is for engine men and 3.1% for firemen.

In considering the substitution of the electric locomotive for the steam locomotive it is obvious that the change eliminates the work which the fireman is employed to perform. The point is frequently made, however, that to reduce the engine crew to one man means an increase in the risk incurred in train operation and this point obviously is of such importance as to require careful consideration.

If we compare conditions which now exist upon such systems as the Manhattan Elevated with the conditions which existed before electricity was adopted, it seems reasonably clear that with a competent motorman operating a controller which instantly cuts off power and applies the brakes in case the hand of the motorman is removed from the handle of the controller, the safety of trains and passengers is assured in higher degree than it was under the old conditions. The usual argument against the elimination of the fireman is of course, found in the allegation that in case of the sudden death or serious illness of the engineman the fireman can take his place and bring the train to a stop or operate it to the next station. The controller which automatically cuts off power and applies the brakes cannot operate the train to the next station, but it can stop it much more promptly than the fireman possibly can, even when he is so located upon the engine as to be in sight of the engineman.

But a very large proportion of our steam locomotives are now designed in such a way that the engineman is not in sight of the fireman, and the mechanism of the steam locomotive which he controls has no automatic device for shutting off power and applying the brakes in case he suddenly dies at his post. In such an emergency on trunk-line railways there would be some advantage in the presence of the fireman, owing to the fact that if competent he could operate the train to the next station. This point might be met by having the train conductor or brakeman or flagman qualified to operate the electric train to its destination in case of accident to the motorman. The degree of skill required, so far as actual manipulation of the mechanism is concerned, would be far less than in the case of the fireman who in emergency might be entrusted with the responsibility of operating the steam train.

It would seem, therefore, that there can be no question of the reasonableness and safety of entrusting the operation of an electric locomotive to one man, provided the control system is equipped with effective appliances arranged to cut off the power and apply the brakes in case the motorman's hand leaves the hand of the controller.

As regards the wages of the engineman, the Manhattan Railway decided to pay its motormen the same wages which it had paid its enginemen. This decision was based largely upon consideration of the fact that familiarity with the road and experience in operating trains under the extremely close headway prevailing upon this system were of such importance that any risk which might be incurred by substituting new men must be avoided. The great majority of electrically equipped railways operating under conditions similar to the Manhattan, however, pay their motormen wages comparable to the wages of the men who operate street cars rather than to the wages of locomotive enginemen.

The work required of the motorman operating an electric train is far less onerous and is performed under conditions much less severe than is the case with the locomotive engine-driver, nor is the motorman in order effectively to perform his duties required to serve years of apprenticeship during which he must become familiar with the complicated mechanism under his control and competent to make upon the road any ordinary emergency repairs. The work required being relatively easy, the apprenticeship comparatively short, and the mechanical knowledge necessary greatly reduced, it is reasonable and proper that the compensation of the motorman, under average conditions, should be less than that of the engineman.

Apart from the attitude to be expected upon the part of employees, and aside from any question of sentiment, however, the management of a railway contemplating the substitution of electricity for steam would not be justified in lowering the standard so far as character and judgment are concerned, which are requisite for the motorman equally with the engineman. It must be remembered also that familiarity with the road and with signals, etc., are as important in his case as in that of his predecessor.

It is impossible of course to fix with definiteness a figure representing the wages of the motorman in railway service as compared with that of the engineman whom he may succeed, but it seems reasonable to assume that under average conditions the services of thoroughly competent motormen can be obtained at a figure which will represent a reduction of 1% in operating expenses, making this item 4.5% instead of 5.5%.

The expense for round-housemen, which under steam operation is about 0.85%, will be greatly reduced both by reason of the reduction in the number of locomotives required for a given service and also by reason of the demonstrated less cost of maintenance per locomotive unit. It is entirely liberal to allow for this item one fourth of its cost in steam operation, the saving here effected being equal to 0.64% of the average operating expenses of steam railroads in the United States.

The estimated cost of the item under consideration, therefore, is 4.71% of total operating expenses.

Item 22, "Fuel for locomotives." One of the marked economies resulting from the substitution of the electric motor for the steam locomotive in railway operation is in the reduction of the fuel account. The cost of fuel upon the average steam railway in the United States for the five years 1901 to 1905 inclusive constituted 11.292% of total operating expenses. The aggregate cost in 1905 was $156,429,245.

The following figures show comparative fuel consumption upon the Manhattan Railway during the year ending June 30, 1901, when steam locomotives were employed and during the year ending June 30, 1904, when electricity was used. During the period first mentioned one pound of coal produced 2.23 ton-miles, if the weight of the locomotive be included, and 1.5 ton-miles, if the weight of the cars only be considered.

During the latter period (electric traction) one pound of coal burned at the power house produced 3.85 ton-miles, excluding weight of locomotives; therefore, the ratio of ton-mileage per pound of coal in favor of electric operation was 2.57 to 1. Including weight of locomotive it was 1.72 to 1.

The average speed under electric operation was approximately 2 miles an hour greater than that attained by steam, and if correction be made for this difference the ratio of ton-mileage per pound of coal excluding weight of locomotives is approximately 3 to 1, and including locomotives 2 to 1 in favor of electric traction. It should be noted also that in this case the coal burned at the power house was of lower grade, and therefore less expensive than that used by the locomotives, and it is reasonable to expect that in general electric traction will mean utilization of cheaper fuel.

We would point out that the argument from Manhattan experience cannot be met by the statement that the Manhattan is not an average railroad. Were the steam and electric apparatus now operating the Manhattan lines applied to the operation of a division of a trunk-line railway, the one part of the system which would be affected in respect to efficiency is the high potential transmission lines, and the effect of their greater length in general would be to increase the relative fuel consumption of the electric system by not more than 5%. For trains drawn by locomotives the fuel account (coal only) under electric operation would still be approximately one-half of the cost of the fuel for steam operation, and for passenger service using multiple-unit equipment it would be less than 40% of the fuel used in equivalent steam service, even if we assume that the system of alternating transmission and conversion to direct current by synchronous converters be employed.

The advantage in favor of electric operation is even more marked if we assume that alternating-current equipment is to be used, as in general would be the case in the electrification of trunk lines or long divisions. In a particular case which we have worked out with great care, the trolley and track rail losses average 3.9%, the load factor being 0.33. This is the result obtained in using the single-phase system for the equipment of a division approximately 40 miles in length, the potential being 11,000 volts. The grand average of traffic in the United States does not exceed seven trains per day passing a given point in each direction, and the trolley and track rail energy losses for this traffic would be less than 2%.

Assuming that such a trolley voltage is used in connection with a feeder potential of say 40,000 to 60,000 volts, the allowable loss in these feeders at maximum load certainly will not exceed 10% and the energy efficiency of step-up transformers, transmission feeders, and step-down transformers will be 92%. Combining this figure with the energy efficiency of trolley and track, as above stated, the resultant efficiency from bus-bars of power house to the train will be 90%.

The works-cost of a kilowatt-hour at the bus-bars of the Manhattan plant is less than 0.6 cent when coal costs $3.00 per ton, this coal having a calorific value of 14,000 B.t.u. per lb. This cost includes fuel, water, labor, maintenance, miscellaneous supplies, and in short everything except capital charges. It is not abnormally low, the cost of both coal and labor being relatively high as compared with the grand average cost of equivalent coal and labor throughout the United States. Where fuel is less expensive, as in the middle West, large modern plants, using steam turbines, are producing the average kilowatt-hour at a price not exceeding 0.5 cent exclusive of capital charges, and in at least one case at a works-cost approximating 0.4 cent.

As will be shown hereinafter, were all the railroads of the United States to be operated by electricity, the average plant required, assuming power to be transmitted 150 miles, would approximate 4,000 kw. if the plants supplied but a single line 300 miles in length. The great bulk of the total power supplied however, would be derived from large plants in which the cost of producing the unit of energy, considering average costs of fuel and labor, should be less than 0.6 cent. While the small plants would exceed this figure we believe that as a grand average 0.6 cent is ample to cover the case. In this connection, it may be remarked that water powers and other sources of cheap power supply would tend to keep down the average cost of power under the assumed condition of electrification of the entire railroad system of the country.

In the case of the single-phase, 25-cycle motor, assuming the average length of run for freight trains to be 15 miles and for passenger trains 20 miles, we have calculated that of the energy delivered to the locomotive approximately 86% will be effective for traction in the case of the passenger locomotive, which is gearless, and about 84% in the case of the freight locomotive, which uses single-reduction gear. Combining the two, it is safe to say that of the energy supplied at the bus-bars in the power house not less than 75% will be effective for traction in the average locomotive equipped with this apparatus.*

The cost of a kilowatt-hour effective for traction therefore is 0.8 cent and the cost of a horse-power hour effective for traction about 0.6 cent of which 0.35 cent is for fuel when coal of 14,000 B.t.u. per lb., costs $3.00 per ton of 2240 lb., and 0.25 cent is for other power-house supplies, power-house labor, and maintenance of power-house equipment.

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*For the motor curves upon which these figures are based, we are indebted to the courtesy of the Westinghouse Electric & Mfg. Co.

As we have stated, the railroads of the United States in 1905 used coal costing $156,429,245. For the purpose of estimating the cost of equivalent electric power the following data are necessary, of which those marked by an * are furnished by the report of the Interstate Commerce Commission while the others involve certain assumptions:

PASSENGER SERVICE

*Passenger train-miles.
Passenger car-miles.
*Passenger-miles.
Average weight of passenger trains:
  a. Weight of locomotives.
  b. Weight of cars.
  c. Weight per passenger.
Average speed of passenger trains.
Average length of run.
*Mail and express train-mileage.
Average weight of mail and express trains.
Non-revenue ton-mileage.

FREIGHT SERVICE

*Freight train-mileage.
*Freight car-mileage.
*Revenue freight ton-miles.
Average weight of freight trains;
  a. Weight of locomotive.
  b. Weight of cars.
Average speed of freight trains.
Average length of run.
Non-revenue ton-mileage, work-trains, switching, etc.

Referring to the several items in the foregoing lists not directly derived from the report of the Interstate Commerce Commission the assumptions made are as follows:

PASSENGER SERVICE

Passenger Car-Miles: These we have calculated from the stated train mileage and the assumption that the average number of cars per train is 5.5.

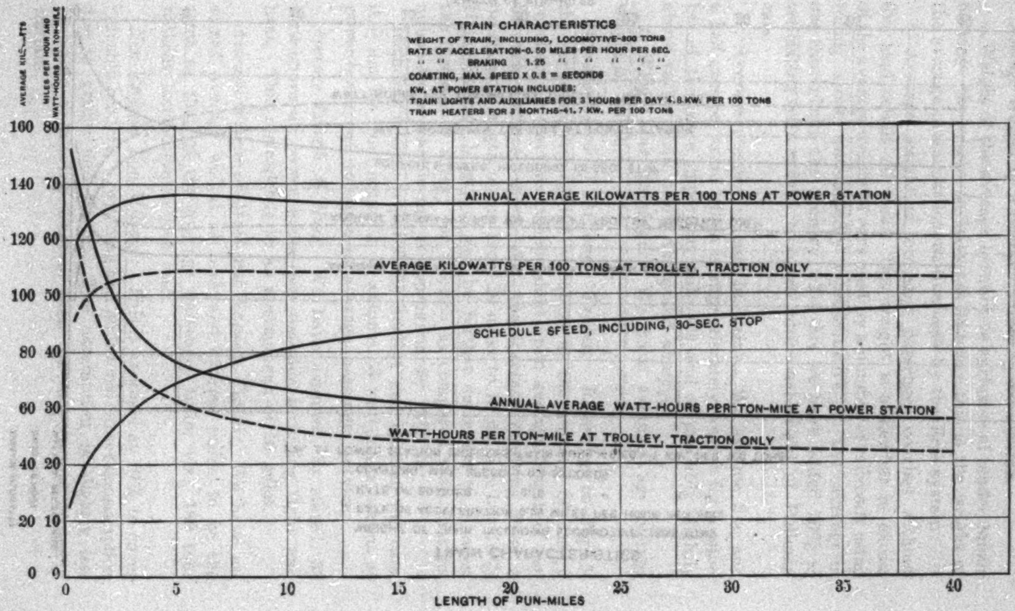
TRAIN CHARACTERISTICS
WEIGHT OF TRAIN, INCLUDING, LOCOMOTIVE-300 TONS
RATE OF ACCELERATION-0.50 MILES PER HOUR PER SEC.
" " BRAKING 1.25 " " " " "
COASTING, MAX. SPEED X 0.8 = SECONDS
KW. AT POWER STATION INCLUDES:
TRAIN LIGHTS AND AUXILIARIES FOR 3 HOURS PER DAY 4.8 KW. PER 100 TONS
TRAIN HEATERS FOR 3 MONTHS-41.7 KW. PER 100 TONS
AVERAGE KILOWATTS
MILES PER HOUR AND WATT-HOURS PER TON-MILE
160 80
140 70
120 60
100 50
80 40
60 30
40 20
20 10
0 0
ANNUAL AVERAGE KILOWATTS PER 100 TONS AT POWER STATION
AVERAGE KILOWATTS PER 100 TONS AT TROLLEY, TRACTION ONLY
SCHEDULE SPEED, INCLUDING, 30-SEC. STOP
ANNUAL AVERAGE WATT-HOURS PER TON-MILE AT POWER STATION
WATT-HOURS PER TON-MILE AT TROLLEY, TRACTION ONLY
0
5
10
15
20
25
30
35
40
LENGTH OF RUN-MILES

FIG. 5.

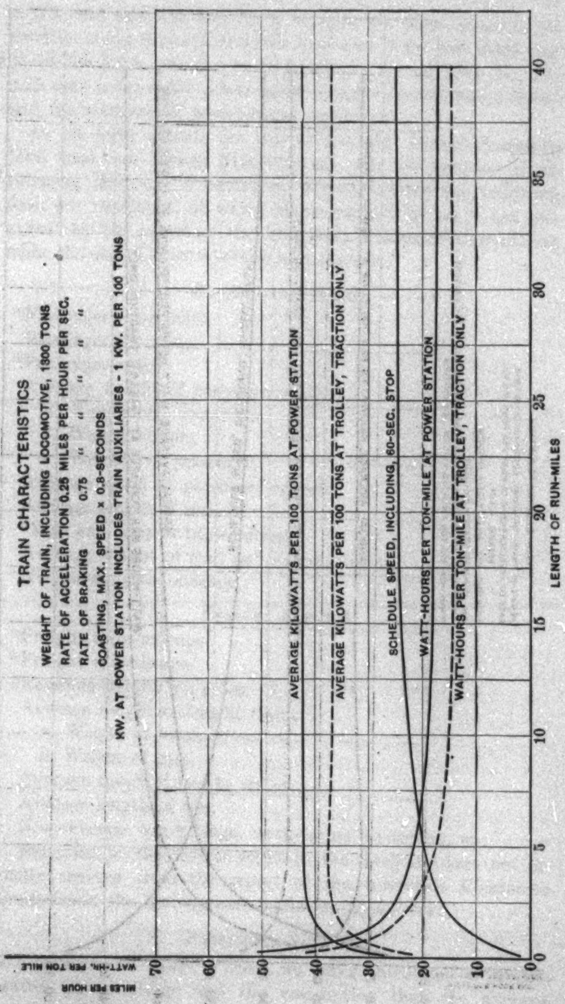
TRAIN CHARACTERISTICS
WEIGHT OF TRAIN, INCLUDING LOCOMOTIVE, 1300 TONS
RATE OF ACCELERATION 0.25 MILES PER HOUR PER SEC.
RATE OF BRAKING 0.75 " " " "
COASTING, MAX. SPEED x 0.8-SECONDS
KW. AT POWER STATION INCLUDES TRAIN AUXILIARIES - 1 KW. PER 100 TONS
AVERAGE KILOWATTS PER 100 TONS AT POWER STATION
AVERAGE KILOWATTS PER 100 TONS AT TROLLEY, TRACTION ONLY
SCHEDULE SPEED, INCLUDING, 60-SEC. STOP
WATT-HOURS PER TON-MILE AT POWER STATION
WATT-HOURS PER TON-MILE AT TROLLEY, TRACTION ONLY
AVERAGE KILOWATTS
MILES PER HOUR
WATT-HR. PER TON MILE
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
LENGTH OF RUN-MILES

FIG. 6.

Average Weight of Passenger Trains: We assume,

a, Weight of the average locomotive exclusive of tender equals 60 tons—the weight on drivers is 38 tons—this is the weight of the average passenger locomotive used by the Erie system;

b, Average weight of ordinary passenger coaches without live load equals 30 tons. This weight is somewhat in excess of the average weight of cars used by a number of railroads using rolling stock undoubtedly representative of the average in use throughout the country. To this we have added 10% in estimating train weight to cover additional weight of Pullman cars.

c, Average number of cars in trains. We assume five and a half cars per train which is approximately correct for a number of the more important railroads and is probably slightly above rather than below the grand average.

d, Weight per passenger. We have assumed an average weight of 140 lb.

Average Speed of Passenger Trains: Referring to Fig. 5, the curve expressing the variation in the amount of energy required for traction as dependent upon average length of run between stations, shows that the increase resulting from a decrease in length of run from 20 miles to 10 miles is but 10%. If the average length of run be further decreased to 5 miles, the increase of energy for traction as compared with that required for a 10-mile run is approximately 18%.

Including energy required for heating and lighting the cars, it is not far from accurate to assume 33 watt-hours output at power-house per ton-mile in average passenger service.

Average Length of Run: We have assumed, as stated, 33 watt-hours at power house per ton-mile including light and heat. This corresponds to an average run of 10 miles.

Average Weight of Mail and Express Trains: We have assumed average weight of mail and express trains to be the same as that of the average passenger train, viz., 180 tons without locomotive or live load.

Non-Revenue Ton-Mileage: This is assumed at 10% to cover "double-headers," switching and additional power consumption due to grades and curves. The assumption is slightly less favorable to electric traction than the facts would probably warrant.

FREIGHT SERVICE.

Average Weight of Freight Trains: As regards freight service, in estimating the average weight of trains we have assumed the following:

a, Weight of locomotives equals 68 tons on drivers. This is the actual average of the freight locomotives of the Erie system exclusive of tender.

b, Weight of cars equals 15 tons. This figure closely approximates the average weight of all freight cars belonging to the Erie Railroad Company.

Average Speed of Freight Trains: Our curves (Fig. 6) are based upon a gear ratio which produces on straight and level track a maximum speed of 25 miles an hour.

Determination of the error involved by any mistake in our assumption of the average speed in freight service is facilitated by Fig. 8, which shows, for example, the following relations:

Maximum Speed.	Average speed, including 60 seconds stop, miles per hour.	Average watt-hours per ton-mile at power station.
20	19	17
25	23	18
30	27	19

Average Length of Run: We have assumed that for all freight service the average length of run is 15 miles. The actual average length of run may vary considerably from the distance assumed without causing material error in our calculation as shown in Fig. 6.

Non-Revenue Ton-Mileage: We have added 15% to the tota revenue earning ton-mileage to cover switching and pusher service and increased power consumption due to grades and curves.

Basing our calculations upon the foregoing statistical facts and the assumptions noted, we estimate that for the operation of the entire freight and passenger service of the United States as existing in 1905, the aggregate energy required at bus-bars of power houses would approximate 13,200,000,000 kilowatt-hours per annum.

At 0.6 cent per kilowatt-hour the total cost of energy for traction, for the operation of all auxiliaries, and for the supply of light and heat to passenger trains would closely approximate $79,000,000 per annum. This figure represents a saving of about

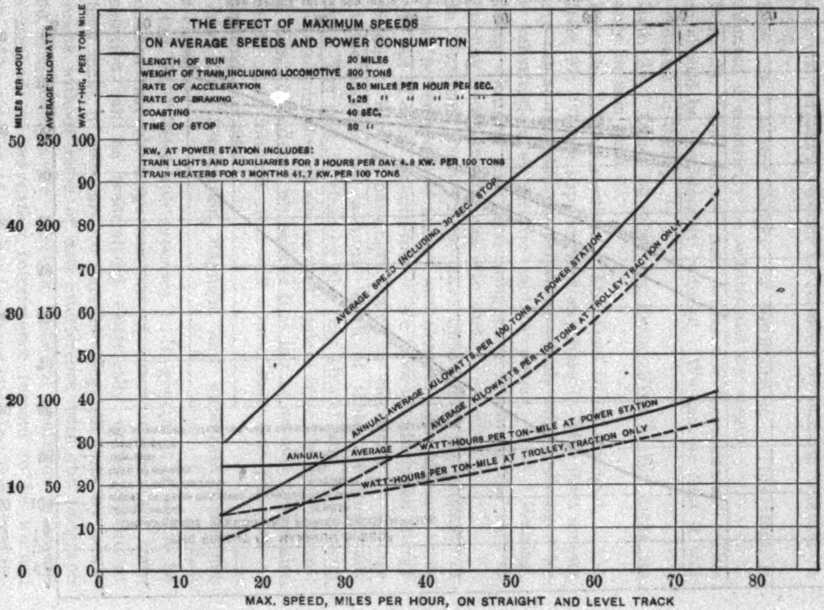
THE EFFECT OF MAXIMUM SPEEDS
ON AVERAGE SPEEDS AND POWER CONSUMPTION
LENGTH OF RUN 20 MILES
WEIGHT OF TRAIN, INCLUDING LOCOMOTIVE 300 TONS
RATE OF ACCELERATION 0.50 MILES PER HOUR PER SEC.
RATE OF BRAKING 1.25 " " " " "
COASTING 40 SEC.
TIME OF STOP 30 "
KW. AT POWER STATION INCLUDES:
TRAIN LIGHTS AND AUXILIARIES FOR 3 HOURS PER DAY 4.8 KW. PER 100 TONS
TRAIN HEATERS FOR 3 MONTHS 41.7 KW. PER 100 TONS
AVERAGE SPEED INCLUDING 30-SEC. STOP
ANNUAL AVERAGE KILOWATTS PER 100 TONS AT POWER STATION
AVERAGE KILOWATTS PER 100 TONS AT TROLLEY, TRACTION ONLY
ANNUAL AVERAGE WATT-HOURS PER TON-MILE AT POWER STATION
WATT-HOURS PER TON-MILE AT TROLLEY, TRACTION ONLY
MILES PER HOUR
AVERAGE KILOWATTS
WATT-HR. PER TON MILE
50 250 100
90
40 200 80
70
30 150 60
50
20 100 40
30
10 50 20
10
0 0 0
0
10
20
30
40
50
60
70
80
MAX. SPEED, MILES PER HOUR, ON STRAIGHT AND LEVEL TRACK

FIG. 7.

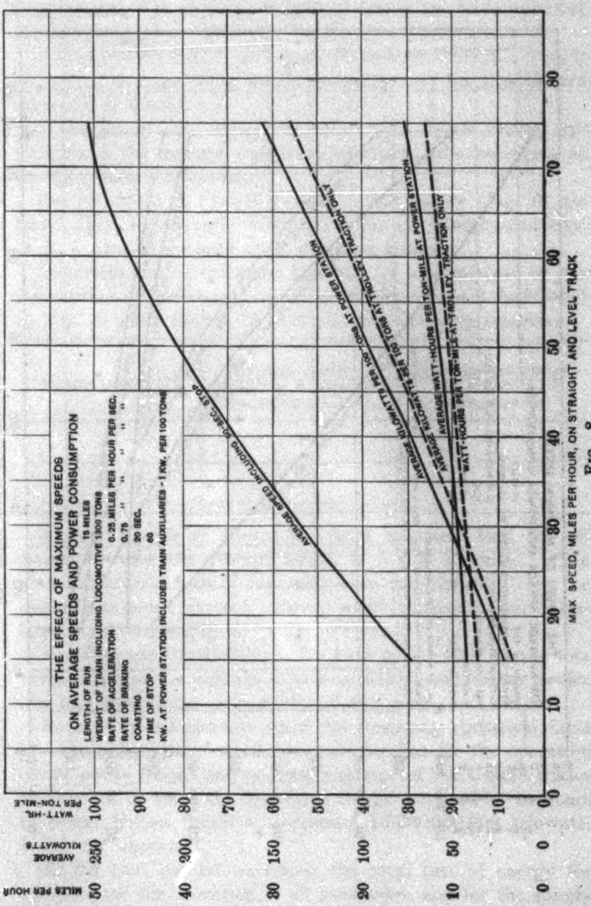
THE EFFECT OF MAXIMUM SPEEDS
ON AVERAGE SPEEDS AND POWER CONSUMPTION
LENGTH OF RUN 15 MILES
WEIGHT OF TRAIN INCLUDING LOCOMOTIVE 1300 TONS
RATE OF ACCELERATION 0.25 MILES PER HOUR PER SEC.
RATE OF BRAKING 0.75 " " " "
COASTING 20 SEC.
TIME OF STOP 60
KW. AT POWER STATION INCLUDES TRAIN AUXILIARIES - 1 KW. PER 100 TONS
AVERAGE SPEED INCLUDING 60-SEC. STOP
AVERAGE KILOWATTS PER 100 TONS AT POWER STATION
AVERAGE KILOWATTS PER 100 TONS AT TROLLEY, TRACTION ONLY
AVERAGE WATT-HOURS PER TON-MILE AT POWER STATION
AVERAGE WATT-HOURS PER TON-MILE AT TROLLEY, TRACTION ONLY
MILES PER HOUR
0
10
20
30
40
50
AVERAGE KILOWATTS
0
50
100
150
200
250
WATT-HR. PER TON-MILE
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
60
70
80
MAX SPEED, MILES PER HOUR, ON STRAIGHT AND LEVEL TRACK

FIG. 8.

$77,500,000 as compared with the coal used by steam locomotives in the year 1905.

Referring to the table, the average cost of this item for 5 years, viz., 11.292%, would be reduced by electric traction to 5.702%.

Item 23. "Water supply for locomotives." This item is eliminated if electricity be substituted for steam.

Item 24. "Oil, tallow, and waste for locomotives." This item should be considerably reduced. We assume that it will be reduced to 0.25%.

Item 25. "Other supplies for locomotives." We make no change in this item.

Item 26. "Train service." This item is not changed.

Item 27. "Train supplies and expenses." This item among many others includes the following which will be changed by the substitution of electric motive power, viz.: "Heating, lighting, cleaning and lubricating cars, including the cost of supplying and pumping gas into cars."

In discussing Item 22, we have included in the estimate of electric power required energy sufficient to light all cars three hours out of every twenty-four. We have also included energy sufficient to heat all passenger trains by electricity an average of three months per annum. Both of these are important items. The cost of cleaning the cars should also be reduced by the elimination of smoke and cinders from the locomotives. All things considered we believe it is fair to assume that under electric operation this item will approximate one per cent. of operating expenses.

Item 28. "Switchmen, flagmen, and watchmen" will not be changed.

Item 29. "Telegraph expenses." In general it is not to be expected that the large amounts of power required for train operation can be transmitted electrically under conditions which make it necessary to parallel telegraph lines by power circuits without more or less interference with the telegraph and telephone service. Certain technical questions in regard to methods of preventing interference remain to be worked out. The erection of overhead circuits carrying power supply will involve generally more or less shifting of the location of the telegraph lines. This item of expense is taken care of in our estimate by inclusion the in cost of overhead construction, and is treated as a capital account.

Telegraph circuits being rearranged with reference to the power circuits, or equipped with one or another of the devices which have been suggested as preventives of difficulties resulting from inductive effects of the power circuits, it might be assumed, perhaps with safety, that Item 29 would not be changed, but we are inclined to the opinion that there will be a slight increase in the cost of this item even under the best plans heretofore proposed, and we therefore increase it in our estimate to 0.2%.

Item 30. "Station service." Examination of the factors constituting this large item indicates no material change.

Item 31. "Station supplies." This item includes among many others the following, viz., "All expenditures for account of heating and lighting depots, waiting rooms, freight and passenger offices and other station buildings; fuel and supplies for engines operating freight carriers on docks, wharves and piers to convey freight between boats and cars; supplies used for stations and yards, signal lights, street lights, switch lights, semaphore lamps, etc., also bills of municipalities for lighting highway crossings."

The ability to employ conveniently for the lighting of important passenger stations and yards, electricity delivered at the point of consumption at a cost which, exclusive of capital charges upon power plant, closely approximates 0.6 cent per kilowatt-hour, to substitute electric motors for engines now used to operate freight carriers on docks, wharves, and piers, and to avail conveniently of electric hoists and telpher systems, are important advantages incident to the adoption of electricity. For lighting and incidental power service of this kind, equivalent to that with which railroads are now apparently satisfied, the change would undoubtedly mean reduction in cost. We will let it stand as it is, however, and would point out the fact that without increasing the cost of this item, a great improvement in facilities for handling freight at docks and wharves and for lighting passenger stations and yards will result from the substitution of electric power.

Items 32, 33, and 34. viz, "Switching charges, balance," "Car per diem and mileage, balance," and "Hire of equipment, balance," will not be changed.

Item 35. "Loss and damage," Under this item the important factors which will be affected by the substitution of electricity for steam are the following: viz., "Charges for loss, damage, delays or destruction of freight, parcels, express matter, baggage and other property entrusted for transportation (including live stock received for shipment) and all expenses directly incident thereto. * * * Charges for damages to or destruction of crops, buildings, lands, fencing, vehicles, or any property other than that entrusted for transportation, whether occasioned by fire, collision, overflow, or otherwise; also services and expenses of employees or others while engaged as witnesses in the case of suits."

For reasons which have been referred to in our discussion of the subject "Safety," it is clear that there should be a material reduction in the charges for loss due to destruction of freight, etc.

Another saving will result from the practical elimination by reason of damage of fire, which now not infrequently is caused by sparks from locomotives.

These savings will be offset to some extent by damage due to telegraph, telephone, or other wires coming in contact with the power circuits of the railway, unless reasonable care be exercised in preventing such accidental contact by the adoption of proper precautions when the electric equipment is installed.

In our estimate we have reduced item 35 to 0.75%.

Item 36. Injuries to persons." "This account includes all charges on account of employes or other persons killed or injured except lawyers' fees and court expenses."

For reasons referred to under the heading "Safety" some reduction in the number of passengers and employes killed and injured in railway accidents may be expected to result from the use of electricity. The risk of fire following collision being materially reduced, we should anticipate a relatively greater reduction in the number of passengers and employees killed in accidents caused by collision or derailment than in the number injured and a reduction in the average severity of non-fatal injuries may also be expected. On the other hand, a certain number of deaths and injuries will result directly from the use of electric power in large amount, by accidental contact with charged conductors. These accidents, however, should not be frequent if care is taken in the installation and proper maintenance of the electric equipment.

In the year 1904, of 10,046 fatal casualties reported by the Interstate Commerce Commission "3,632 were sustained by employes, 441 by passengers and 5,973 by other persons. Of this last number 5,105 were reported as trespassing, from which it may be presumed that the railways are in no sense legally responsible for the deaths in question; suicides are included in this class."

"The number of injuries sustained by employees during the year was 67,000. The number of injuries sustained by passengers was 11,111 and the number of injuries sustained by persons other than passengers and employees was 7,977."

As regards the expenses included under item 36, we have no data indicating how these are divided other than the fact that the railroads apparently were put to little if any expense on account of about 80% of those persons other than passengers and employees who were killed and injured. While it is probable that a large part of the expenditures was on account of passengers killed and injured, and while any reduction in fatal and serious accidents to passengers therefore would materially affect this item, we have thought it best in the absence of satisfactory data to leave it practically as it stands, our estimate being 1%.

Item 37. "Clearing wrecks." In our opinion this item will be reduced under electric operation for reasons which have been sufficiently indicated in what we have said in regard to item 35. It would seem that 0.2% is a fair estimate of its probable amount.

The following items will not be changed:

Item 38, "Operating Marine Equipment."
Item 39, "Advertising."
Item 40, "Outside agencies."
Item 41, "Commissions."
Item 42, "Stock yards and elevator."
Item 43, "Rents of tracks, yards and terminals."
Item 44, "Rents of buildings and other property."
Item 45, "Stationery and printing."
Item 46, "Other expenses."

General Expenses

As regards the several items included under the heading "General expenses," the adoption of electricity will cause no material change.

Summary and Conclusions.

Our approximate estimate of the expenses chargeable to operation if electricity were in use to-day for the operation of all the railways in the United States, as discussed in the foregoing pages, is recorded in detail, item for item, in the last column of the tabulated data in Table I; these data with the exception of this column of estimates being the official records of the reports of the Interstate Commerce Commission. When considered in detail, the estimates are naturally subject to criticism more or less destructive, as in respect to many items we have not found opportunities to secure and investigate the great mass of detailed data showing in segregated form the scores of factors which are included in the aggregates appearing as single items in the summarized table of operating expenses; but while recognizing fully the imperfections and incompleteness of the attempted comparative analysis, we believe that the conclusions reached are correct within a reasonable degree of approximation.

According to our estimate, if all the railways of the United States were to-day operated by electricity using the single-phase alternating-current system at the potential adopted for the equipment of the New Haven Railroad, the energy required for operation being developed by power plants such as are to-day in extensive use and transmitted at potentials well within limits established in practical service, and if the rolling stock equipment consisted of locomotives and multiple-unit trains fitted with motors and control apparatus no better than the best which now exist, the aggregate cost of operation which in 1905 amounted in round numbers to $1,400,000,000, would be reduced by about $250,000,000.

To accomplish this result, power plants delivering about 13,200,000,000 kilowatt-hours per annum would be required. Assuming the radius of transmission from power houses to be 150 miles, the load-factor in railway service should be not less than 0.75, and taking this figure it appears that power plants capable of delivering a maximum output of about 2,800,000 kilowatts will be sufficient to operate the entire railway service of the United States as existing in the year 1905. The average output required is about 10 kilowatts per mile of line and 7 kilowatts per mile of track.

In 1905 the average gross earnings of our railroads per mile of line were $9,598, and the average operating expenses $6,409. The foregoing calculations lead to the conclusion that high-class electric equipment now available would reduce this average cost to $5,265. The difference is $1,144 per mile of line, against which apparent saving must be charged the annual interest and depreciation of the power plant, the addition to permanent way equipment, comprising overhead construction and track bonding, the transmission circuits, and the sub-stations with their equipment. Assuming 5% interest on cash cost of these items and allowing 5% for a sinking fund to cover depreciation of power house with its equipment and 2½% for a sinking fund to cover depreciation of the overhead construction and distributing system, the aggregate of fixed charges works out at $837 per mile of line. The saving in operating expenses, therefore, is more than sufficient to take care of the increase of fixed charges. In other words, it appears that the entire railroad system of the United States could be operated to-day at less cost by the electric motor than by the steam locomotive. That the railroads in general if so equipped would realize a large increase in earning power will be admitted by all who have given the subject intelligent attention.

In charging against electric operation 5% upon cost of power plant and 2.5% upon overhead construction, transmission circuits, substations, and track bonding, we have departed from methods usually adopted in financing American railway properties. If no depreciation be charged against the increased capital account represented by the items named, the apparent saving will be materially increased.

While our estimates have led us to the conclusion that, under average existing conditions of railway operation in the United States, improved financial results would be attained by the substitution of the electric motor for the steam locomotive, the immediate and general adoption of the new motive power by our railroad companies is neither possible or desirable. It requires no argument to demonstrate the wisdom of making haste with deliberation in a matter involving interests of such magnitude as those which are tied up with the transportation systems of the United States. Recognizing the magnitude of these interests and having in mind the fact that the art of electric traction as applied upon a large scale to heavy train units is yet young, the point which we desire here to emphasize is the necessity of conservative and carefully considered action upon the part of all members of this Institute who may be called upon to advise in respect to the electrification of railways now operated by steam.

Referring to the following tabulated results, in which we have applied the estimated reductions in operating expenses under electric traction, amounting to 18% of the present average operating expenses to the ten geographical groups into which the railroad systems of the United States are divided by the Interstate Commerce Commission, the relatively great advantages of applying electric traction to systems operating heavy traffic showing large gross earnings per mile of line are evident at a glance.

TABLE II.

COMPARISON PER MILE OF LINE—BY GROUPS STEAM AND ELECTRIC OPERATION.

(216,974 Miles Represented.) (Dollars per mile of line per year.)

Group No.	General Location	Miles of Line Represented	Gross Earnings	(Steam) Operating Expenses	(Electric) Operating Expenses	Difference Steam and Electric Operation	5% interest on Electrical Equipment Excluding Rolling Stock.
I	New England	8,094	$14,511	$10,493	$8,604	$1,889	$647
II	New York, Pa., et al.	23,281	20,752	13,671	11,210	2,461	790
III	Ohio, Ind., Mich.	25208	12,483	9,198	7,542	1,656	640
IV	Virginias, N. and S. Carolina	12,542	7,359	4,590	3,764	826	484
V	Kentucky, Fla., Louis, et al.	24,563	6,867	4,899	4,017	882	475
VI	Ills., Wis., Dakotas, Ia., et al	48,672	8,021	5,169	4,239	930	525
VII	Mont., Neb., and Wyoming	11,546	7,737	4,092	3,355	737	461
VIII	Colo., Ark., Missouri, et al	30,456	6,362	4,308	3,533	775	461
IX	Texas and New Mexico	14,875	5,588	4,108	3,369	739	445
X	Pacific States	17,737	8,439	4,880	4,002	878	464
	United States, Total	216,974	9,598	6,409	5,255	1,154	516

THE STANDARDIZATION OF ELECTRIC RAILWAY TRACTION EQUIPMENT

Electricity, entering the field hitherto occupied exclusively by the steam locomotive, encounters conditions which greatly emphasize the necessity of prompt standardization of engineering practice. The management of our railways, beginning by electrifying terminals, tunnels, and mountain-grade divisions, will inevitably be led to extend these zones of electrification until they include divisions of very considerable length, and even trunk-line systems. To call attention to the transcendent importance of standarizing the location of such additions to permanent way equipment as the overhead trolley conductor and the third rail, is to demonstrate its necessity.

Electrical engineers now generally recognize the great value of established standards of frequency and potential in plants installed for lighting and power purposes. In recent years, the Institute, through its Standardization Committee has done splendid work for the manufacturer of electrical apparatus, as well as for the investor, by using its influence to promote the adoption of standards. Not many years ago, however, manufacturing companies, and consulting engineers, were in many cases prone to put forward or specify apparatus without reference to its ability to operate effectively in conjunction with other central station equipment, even when the latter was in actual operation in the immediate vicinity of the new plant. Fortunately, this tendency was less marked in the United States than it was, for example, in Great Britain. What will happen from a failure to adopt standards of practice at an early stage in the development of an industrial art of this nature, is well illustrated by the problem now presented in London, where the engineering advisers of the London County Council are engaged in studying the problem—how to supply electricity in bulk to 62 central-station plants producing electricity in bewildering variety of frequency and potential.

In the railway field, obviously, general principles are the same as in lighting; but wise foresight is more necessary and failure to exercise such foresight at this date less excusable. Moreover, the advocates of electric traction, unlike those who introduced the electric light into commercial service, are called upon to deal with a great body of trained engineers and experienced managers who are engaged in operating and extending systems of transportation which challenge admiration and respect. The rolling stock equipment of our railways, as a whole, is justly an object of national pride. The engineers and managers directing and controlling these properties are probably the equals of any body of men in the world as regards intelligence and experience. Obviously, it is of the utmost importance that they who accept the responsibility involved in the substitution of electricity for steam in the operation of certain parts of our great railways, should avoid fancies or fads and should in every way coöperate in the great work of evolving promptly standards of electric railway practice which shall withstand the test of time. The comparatively small beginnings of to-day will in all probability extend with a rapidity which we cannot now realize, and the confusion and loss which will inevitably result in the near future, if a variety of electric equipment be grafted at different points upon the existing railroad systems now operating by steam, may be imagined. The trouble and expense caused some years ago by the existence of several gauges of railway track in America were as nothing compared with what may result from a failure to establish promptly standards of practice in the field of electric railway traction.

Where to-day are the "16,000 alternation" system of lighting, the "15,000 alternation" system of lighting, the "constant-current alternating-current arc light system," the "40-cycle system" and the "monocyclic system?" Where ten years from to-day will be the 1200-volt, or the 1500-volt, direct-current systems which have been suggested as substitutes for high-potential alternating-current systems in heavy electric traction?

While emphasizing the great importance of the early establishment of standards in the field of heavy electric traction, it must be recognized clearly that further inventions are liable at any time to modify views based upon present knowledge. The work of standardizing, therefore, should proceed with caution; but surely if present knowledge, not only of existing apparatus but of the lines along which applicable improvements must take place, is not sufficient to justify conservative application of the principle of standards, it is not sufficient to justify the investment of the very large sums which are now being expended for electric equipment.

Engineers constituting the membership of this Institute owe it to themselves, as well as to their clients, to use every effort without prejudice and without fad, to prevent waste by opposing the introduction of apparatus which, from its limitations, cannot solve the general problem of railway electrification; and it is to be hoped that they will use their united influence to fix proper standards as rapidly as this establishment may be consistent with progress.

Fortunately, knowledge of the possibilities and limitations of electric apparatus to-day is a very different thing from what it was in the early days of electric lighting. At the present time we have available theory so complete that electric science is less exact only than the science of astronomy and in applying this science in constructive work agreement between results carefully predetermined by calculation and those realized in practice is far closer than in any other comparable branch of engineering. There can be no doubt that it is possible to-day, in passing upon such a question, for example, as that of best frequency for railway operation to make a choice which shall withstand the test of time.

The necessity of proper standardization is obvious. Specifically, it would seem feasible and eminently wise to agree upon standards of practice in respect to the following:

a. Location of third rail.

b. Location of overhead conductor used with single-phase alternating-current system.

c. Frequency of alternating-current traction systems.

It is equally desirable, but probably less easy, to agree upon a standard system of multiple-unit control for train operation.

THE QUESTION OF FREQUENCY.

While appreciating throughly and desiring to emphasize the importance of establishing and maintaining standards, it is also of the greatest importance that standards should be wisely chosen. The choice should be made, if possible, with full knowledge of the essential factors involved, and correct perspective view of their relative importance. It is with the feeling that so far as the frequency 25 cycles per second may be said to have become established, considerations obvious at first glance, but not properly controlling, may have influenced the choice unduly that we desire to present for discussion, the very important question whether 25 cycles per second or a lower frequency; *e.g.*, 15 cycles per second, is best adapted and should be established as a standard in the equipment of railways by electricity.

Final decision of such a question should be left neither to manufacturing companies, the management of which may be unduly influenced by commercial considerations, affecting their own immediate prosperity or convenience, nor should it be left to the individual consulting engineer. It is precisely the kind of question which the Institute should pass upon by the adoption of a recommendation carefully considered by its Standardization Committee. The manufacturing companies, which are largely and very influentially represented in the body of the Institute, will doubtless be willing to coöperate in the collection and study of the facts requisite to the formation of a well-grounded report.

While the adoption of a standard by the Institute has the force only of a recommendation, the American Railway Association perhaps might deem it wise to indorse the choice of the Institute. Such action on the part of these two bodies would go far definitely to establish the standard.

Comparing the relative advantages of 25-cycles and 15-cycles in railway service the salient advantages of the former are the following:

1. It is to-day in extensive use in plants developing and distributing energy for lighting and power purposes, and through sub-stations equipped with converters for the operation of many interurban lines. It has been adopted on a very large scale by such companies as the Interborough Rapid Transit Company of New York for the operation of its subway, surface, and elevated lines, by the Pennsylvania & Long Island Railway Companies for the electrification of New York terminal service and operation over a considerable part of Long Island, and by the New York Central for the electrification of its terminal service It is also the frequency developed by all of the great power plants at Niagara Falls, and from this source of power it is possible for all railway lines within a radius of 150 miles, or an even greater distance, to procure an ample supply of very cheap power.

It has been adopted by the New York, New Haven & Hartford Railway Company, the pioneer among American railroads in the adoption of the alternating-current motor in heavy railway traction, and by the Grand Trunk Railway for the electrification of the Sarnia Tunnel. Alternating current at 25-cycles is also utilized without the interposition of converters by the motor equipment on a dozen or more interurban trolley lines.

2. Our great manufacturing companies have drawings, patterns, and dies which enable them to manufacture conveniently and promptly practically all power-house and sub-station equipment required for 25-cycle apparatus. The weight of this consideration, however, is somewhat lessened by the fact that the march of progress—just now greatly accelerated by the general adoption of steam turbines—will undoubtedly cause a large proportion of existing drawings and patterns to be superseded probably in the very near future and certainly within the next five years.

3. The 25-cycle system is preferable to the lower frequency in the design of turbo-generators, since it affords wider range within which to select speed for units of various outputs. For very large units a frequency of 15-cycles, for example, requires either a 2-pole generator operating at 900 rev. per min., a 4-pole generator operating at 450 rev. per min., or a 6-pole generator operating at 300 rev. per min. Reduction in the number of revolutions per minute implies increase in diameter of the revolving element of generator and turbine, and in machines of large output the diameter of the revolving element in turbines of certain types may become too large for shipment in view of the limitations imposed by tunnels.

4. A frequency of 25 cycles permits convenient and effective lighting of yards and shops by incandescent lamps. It is also more favorable than a lower frequency as regards operation of induction motors for shop purposes.

Should our railways in general be equipped for electric operation, it is to be expected that in many cases they would undertake to supply electricity for light and power purposes beyond their own requirements, and the higher frequency possesses important advantages with reference to such commercial service.

For lighting and general power purposes in cases where service for lighting purposes that shall be thoroughly satisfactory in respect to voltage, regulation and continuity is requisite, commercial supply at 25 cycles would be preferable. Through the interposition of motor-generator sets or converters in combination with storage batteries in such cases either frequency is applicable.

5. The higher frequency possesses some advantage in respect to the ratio of tractive effort to weight upon drivers. The best information available to date appears to indicate that the difference between 25 cycles and 15 cycles in respect to

this consideration probably approximates 10%. Further data from actual test are desirable, and must be obtained before it is possible to estimate closely the weight of advantage possessed by the higher frequency.

6. The higher frequency is preferable for induction motors in railway service requiring a considerable range of speed adjustment. The force of this consideration depends upon the probability of using induction motors for traction purposes, and applies not only to the excellent three-phase motors, such as are in very successful use upon the Valtellina line, but also to the single-phase induction motor which, perhaps, is not beyond the range of probability. It is probable that in any general electrification of our railway system, induction motors will play a part by no means unimportant.

Without attempting detailed discussion, it is evident from the foregoing brief statement of the more important considerations in favor of 25 cycles that extremely weighty reasons must exist if the adoption of a lower frequency, *e.g.*, 15 cycles, is justified.

While our object in raising this question of frequency is to present it for discussion with a view to securing additional data and, if possible, a careful consideration of this very important question by the Institute through its Standardization Committee, or a special committee, and while we desire to avoid anticipating the verdict resulting from such an investigation, it is proper to state here that consideration of the facts now available leads us to conclude that notwithstanding the number and force of the arguments in favor of 25 cycles, a frequency of 15 cycles is preferable and should be adopted for heavy electric traction. The fundamental and, as it would appear, controlling reason which leads to this conclusion is the fact that within given dimensions a materially more powerful, efficient, and generally effective single-phase motor can be constructed for 15-cycle operation than is possible if 25 cycles be selected.

Final decision of the question whether the advantages of the 15-cycle motor as compared with the 25-cycle motor in respect to dimensions, weight, efficiency, power-factor, and commutation are such as outweigh the many and important considerations which favor the higher frequency, requires more complete data than we have been able to secure up to the present time. That the difference is material, however, is established not only by general theoretical consideration of the effect of a reduction in frequency upon the design and performance of single-phase commutating motors, but also by the following facts:

1. In the case of multiple-unit equipment of passenger cars where locomotives are dispensed with and motors carried upon the car trucks, it is very important that the dimensions of motors be reduced to a minimum. Cars weighing, say, 35 tons without equipment and operating on straight and level track at speeds of from 60 to 70 miles an hour, require but two motors, except as it may become necessary to employ four motors by reason of lack of sufficient clearance at cross-overs. The difference between a two-motor equipment and a four-motor equipment in such a case approximates $2,500.00 per car, besides which the four-motor equipment adds materially to weight, practically doubles complication, and, for both of these reasons, increases cost of operation. The difference between the dimensions of a 15-cycle and a 25-cycle motor may easily be the controlling consideration compelling the adoption of the four-motor equipment.

2. In the application of single-phase commutating motors to locomotives in general railway service, the minimizing of motor dimensions is perhaps still more important, although in this instance the limitations imposed by the space available are less obvious.

High-speed passenger locomotives at least should be gearless. For any assumed limits of weight per axle and length of wheel-base, that frequency is preferable which permits the construction of a motor which will exert the greater pull at the draw-bar, provided efficiency, commutation, and power-factors are substantially equal.

Those who are engaged directly in the design of single-phase motors are probably in position to contribute to the discussion of this paper data which will throw much light upon the subject; but it would seem probable that within given limits of dimensions, 15-cycle motors would materially surpass 25-cycle equipment in this respect. We are inclined to this opinion notwithstanding the probable advantage of 25-cycle equipment as regards the ratio of effective draw-bar pull to weight upon drivers.

3. There can be no question of the superiority of the 15-cycle motor in respect to the very important features, commutation, efficiency, and power-factor. Efficiency is obviously and directly important. Power-factor affects the efficiency of the

entire system from the motor to, and including, the generator. Commutation, in view of the large and expensive commutators and the brush complication of this type of motor, is of great importance.

In order that the question raised may be looked at in proper perspective the following estimates based upon foregoing calculations will be useful:

For the equipment of the entire railway system of the United States as now existing an aggregate power-house output capable of supplying continuously 2,100,000 kilowatts would be required. Of the electric apparatus installed in the power-houses, a change in frequency affects the generators, transformers, and a large proportion of the measuring and indicating instruments. It also affects the cost of the engine or turbine employed to drive the generator. At 25 cycles, the apparatus affected by frequency should cost approximately $30 per kilowatt. At 15 cycles it would cost on the average perhaps $33 per kilowatt. Cost of sub-station transformers would be increased approximately one-third, and, in round numbers, the total cost of turbines and electrical power house and sub-station apparatus would be increased from $70,000,000 to $80,000,000.

If it be assumed that one electric locomotive will do the work of two steam locomotives, about 24,000 electric locomotives would be required to take care of the present railway business of the country. Assuming the cost of the average electric locomotive to be $25,000 the aggregate cost of locomotives required would be $600,000,000. Allowing for the increased cost of the 15-cycle transformers, it would seem that the difference in cost of the average locomotive should be not less than $1,000 in favor of the lower frequency, or for 24,000 locomotives $24,000,000. This is more than twice the estimated difference in cost of power-house and sub-station equipment.

It seems entirely safe to say, therefore, that the aggregate first cost of electric equipment and of steam turbine will be decreased by a change from 25 cycles to 15 cycles. The operating cost will obviously be decreased very materially. At least three-fourths of the above estimated cost of electric locomotives, say $450,000,000 represents cost of electric equipment. It will be seen, therefore, that of the apparatus which our electrical manufacturing companies may be called upon to furnish, more than 85% is rolling stock. Obviously, any argument in favor of 25-cycle equipment which may rest upon existence of drawings and patterns and convenience in manufacturing should have comparatively little weight.

The use of 15 cycles instead of 25 cycles also secures considerable advantage in respect to the overhead trolley conductor and track return. With a given limit of voltage-drop, this advantage may be utilized by reducing size and, consequently, cost of the overhead copper and the copper used to reinforce the track return.

Under the plans which we have assumed as a basis of our calculations, the amount of copper required for feeder circuits, trolleys, and reinforced track-return, estimated at 20 cents per pound would cost approximately $750,000,000 were the entire railway system of the country as existing in 1905 to be equipped for electric operation.*

We desire to acknowledge with appreciation, assistance kindly rendered in the collection of data for this paper by Mr. J. M. Graham, vice-president of the Erie Railroad Company; Mr. Theo. N. Ely, chief of motive power of the Pennsylvania Railroad Company; Mr. George Gould, president of the Missouri Pacific and other railway systems; Mr. E. Z. Jeffrey, president of the Denver & Rio Grande Railroad Co.; Mr. E. P. Bryan, vice-president and Mr. Frank Hedley, general manager, of the Interborough Rapid Transit Company; Mr. G. Leve, of the Railway Electric Power Company; Mr. Alvan Markle, president of the Wilkes-Barre & Hazleton Railway Company; Mr. George C. Smith, vice-president of the Security Investment Company; Mr. H. J. Pierce, president of the International Railway Company; Messrs. Conwell, Shepard and McLaren, of the Westinghouse Electric & Manufacturing Company; and Messrs. Potter and Mahony, of the General Electric Company.

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*In all our estimates we have included 0000 copper conductor in the return circuit, this being bonded to the rails at intervals for the purpose of preventing dangerous potential on track in case of a broken bond.

APPENDIX

Power-House Output and Load-Factor

The report of the Interstate Commerce Commission gives the total revenue traffic for the entire United States for the year ending June 30, 1905, as 1,038,441, 430 train-miles, of which 459,827,029 is passenger-train mileage, 546,424,405 freight-train mileage, and the unclassified balance, 32,189,996, we have assumed to be mail- and express-train mileage. Including the mail and express trains with the passenger-train service, there is an average of 6.2 passenger and 6.9 freight trains per mile of line per day, or approximately 7 trains each way per day.

Using average weights of equipments, as stated in our paper, and average hauls of goods and passengers, and making allowances for switching, etc., the traffic amounts to 3,000,000 ton-miles per mile of line per annum, of which 600,000 ton-miles are in passenger service and 2,400,000 ton-miles in freight service. In electric operation these figures will be reduced by the weight of engine tenders and a part of the weights on pony trucks.

To supply electric power for the operation of the steam roads, we have assumed that power houses would be located at average intervals of 300 miles. This requires a transmission of 150 miles and for this purpose we have employed in our calculations 60,000 volts. As stated in our paper, both the distance of transmission and the voltage employed are within current practice in plants now in commercial operation in this country, under conditions and for purposes identical with those contemplated in our paper.

In our calculations we have assumed that passenger trains are geared for a maximum speed of 50 miles per hour and freight trains 25 miles per hour, on a tangent and level track. We have assumed that the average run of passenger trains is 10 miles and freight trains 15 miles between stops. With the gear ratios used this gives an average speed of 40.5 and 23 miles per hour, respectively. At these speeds the average load on each power station supplying 300 miles of line is 1.98 passenger trains and 3.84 freight trains, an average of 5.82 trains of both kinds. With equal intervals between passenger and freight trains, respectively, the average load on the power house is 2100 kw., the load-factor is 0.97 and the maximum momentary peak is estimated to be 3000 kw. This method of operation is shown in **Fig. 9.**

The schedule speeds above mentioned include momentary stops only. As trains are now operated, the average passenger train, owing to stops and delays of various kinds, does not average more than 30 miles an hour, and through and local freight trains probably do not average more than 12 miles an hour. In Fig. 10 we have illustrated the result at the power house if trains are operated at these modified average speeds. The average load remains practically the same as before, while the load-factor is reduced to 0.82 and the estimated maximum momentary peak is increased to 4700 kw.

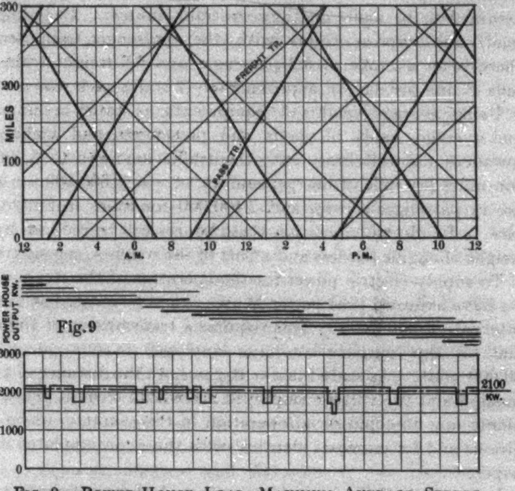

Fig.9

FIG. 9.—POWER-HOUSE LOAD, MAXIMUM AVERAGE SPEEDS.
Passenger trains, 226 tons, 40·5 miles per hr. 273 kw.
Freight trains, 937 tons, 23.0 miles per hr. 351 kw.
Transmission efficiency 90%. Average trains on section, 5.8.
Average power-house load 2100 kw. Load-factor 0.968.
Estimated momentary peak 2970 kw., 85% efficiency.

Our estimate of the total power-house capacity for all the railroads of the United States is 2,100,000 kw., which is approximately 3,000 kw. for each 300-mile section. This is nearly 50% in excess of the average load. The generators proposed for this power-house equipment have a momentary overload output of

100% and can carry an overload of 50% for several hours. It is evident, therefore, that the average power plant provided, after deducting 20% for reserve, is ample to take care of ordinary variations in traffic.

It is manifestly impossible for railroads to operate their passenger and freight trains on equal headway. Some roads as a matter of convenience despatch freight trains in " fleets ", and

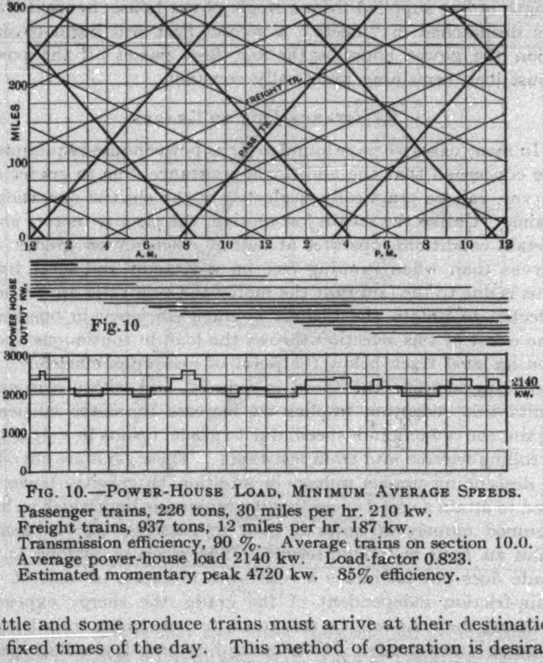

FIG. 10.—POWER-HOUSE LOAD, MINIMUM AVERAGE SPEEDS.
Passenger trains, 226 tons, 30 miles per hr. 210 kw.
Freight trains, 937 tons, 12 miles per hr. 187 kw.
Transmission efficiency, 90 %. Average trains on section 10.0.
Average power-house load 2140 kw. Load factor 0.823.
Estimated momentary peak 4720 kw. 85% efficiency.

cattle and some produce trains must arrive at their destinations at fixed times of the day. This method of operation is desirable and practicable in steam operation and obviously is objectionable in electric operation, as power-house capacity must be provided for the maximum number of trains on the division. On the other hand, on those roads where traffic is most congested, the track facilities can best be utilized by equal spacing of trains. When this question becomes important, therefore, the natural tendency is towards an approximately equal distribution. As the generators include in our estimates have a continuous overload capacity of 25%, 50% for several hours, and 100% momentarily, and as we have provided an excess of nearly 50% over average demands, the power-house capacity provided appears ample for any reasonable variation in the method of operating trains. In this connection, we wish to call attention to the fact that under average conditions freight trains require 25 hours to traverse the length of line supplied from a single power house; hence if trains are despatched in "fleets" a second fleet will begin to draw upon the power house as the first fleet passes off the power-house load remaining practically constant.

RESISTANCE DUE TO GRADES

In many cases we have found so far as power house-requirements are concerned that the additional resistance, due to grades and curves, can be practically neglected in the electric operation of trains. Unlike the steam locomotive, the electric motor, under certain conditions, operates at higher efficiency on grades and curves than when running free on a straight and level track. This is due to the fact that the motor and gear ratio are properly selected to obtain the highest average efficiency in operation. The effect of this selection throws the load in continuous operation on level track below the point of maximum efficiency. In ascending a grade the speed is reduced, and within reasonable limits this reduction implies an increase in motor efficiency. Again, the reduction in speed, due to grade, results in a reduction in rolling friction and train resistance. These gains are not offset in descending grades unless, in addition to gravity, power be used to attain a speed exceeding the maximum limit which we have assumed, namely, 50 miles an hour in passenger service and 25 miles an hour in freight service. Theoretically, as long as the grade does not introduce a resistance in excess of that of the train-friction independent of the grade, the energy expended in lifting the train will be recovered in overcoming train-friction in going down grade. If the ascending and descending speeds are equal the energy consumption will be the same per ton-mile as on a straight and level track of the same length. If the ascending speed is reduced, as it is in the case of the series motor, the total watt-hour consumption will also be reduced. In Fig. 11 and Fig. 12 we have plotted the effect of grades upon power consumption in both passenger and freight service. In order to keep this discussion distinct from the question of motor and transmission efficiencies, we have assumed a motor efficiency of 85% in all cases and 90% transmission efficiency. All power calculations are carried back to the power house, and that portion of the recuperated energy which cannot be utilized by the train auxiliaries has been returned to the power house at 90% efficiency. Extra electric locomotives are added as needed. With the train weights employed, it will be noted from an inspection of these curves that the power consumption over grades is less than it is over straight and level track in passenger service for all grades less than 0.55%, and in freight service less than 0.35%. Comparatively few lines are absolutely level, but on the other hand the aggregate mileage on grades exceeding 0.5% is relatively small. It is believed, therefore, that the general result as to power consumption will be very close to that required over straight and level track. Nevertheless, as stated in our

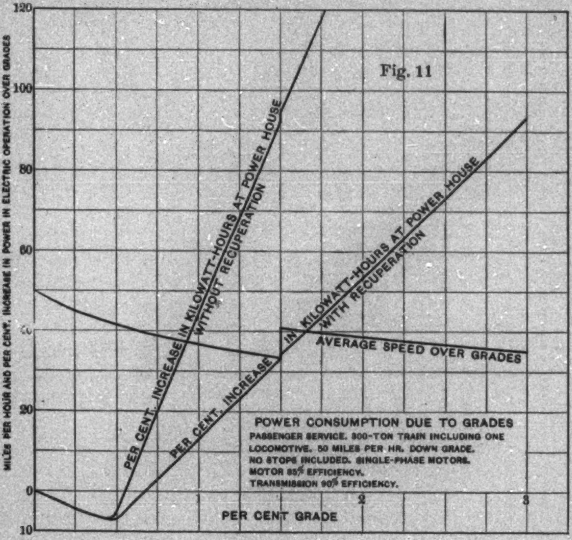

Fig. 11.

paper, we have added to our calculations of energy required 10% in the case of passenger service, and 15% in case of freight service, to cover contingencies, including switching, "double headers" and the additional resistance due to grades and curves.

In some recent calculations in which we went into the subject in great detail the foregoing conclusions were corroborated. In one case in express service the detailed calculations of runs over the road showed a consumption of power of 53 watt-hours per ton-mile, while 52.8 watt-hours per ton-mile was obtained by using an average run on a straight and level track. In the local

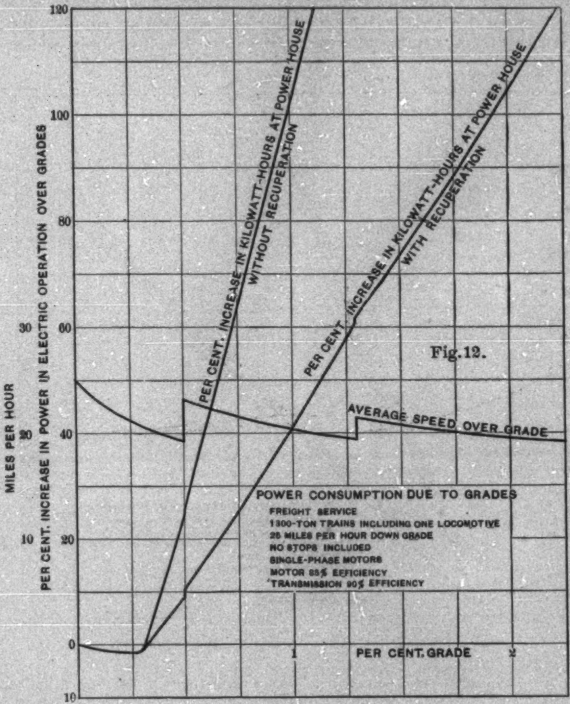

Fig. 12.

service over the same line the figures were 84.2 watt-hours in the detailed calculations and 86 watt-hours for an average run on a straight and level track. These results were obtained from calculations relative to the electrification of the suburban portion of a steam railroad over 30 miles in length; a large percentage of its tracks being on grades and curves. There were maximum grades of 1.47%, 1.55%, and 2.32% and curves of 6° 22′ and 8° 30′. Numerous other calculations and road tests have verified these results.

RECUPERATION.

In making our calculations as to power consumption, we have made no deduction for the electrical return of power to the line. In the case of the higher grades this becomes a matter of importance, as shown by Fig. 11 and Fig. 12. Where the force of gravity due to grade exceeds the amount that can be utilized mechanically in overcoming train-friction, recuperation reduces the increase in power consumption due to the grade by approximately 60% over a grade of 1.5%, so that even in freight service over mountain grades the power required will not exceed that consumed on a level track by more than from 40% to 60%. With recuperation, the power consumption or what is its equivalent, the coal consumption, is not doubled until we reach grades of over 3% in passenger service and 2% in freight service. These grades are considerably in excess of any used on our trunk-line railroads. The ability to recuperate energy is important on lines that have heavy grades. In addition to the saving in power, the saving in wear and tear from mechanical breaking is of as great, and perhaps even greater, importance. The energy represented by the difference between the curves shown on Fig. 11 and Fig. 12 representing the power required at the power house with and without recuperation, increased by the energy losses absorbed by the motor and transmission lines, must be absorbed by the brake-shoes and wheels when mechanical braking is used.

DISCUSSION ON "ON THE SUBSTITUTION OF THE ELECTRIC MOTOR FOR THE STEAM LOCOMOTIVE," AT NEW YORK, JANUARY 25, 1907.

Frank J. Sprague: This paper has evidently been prepared with a good deal of care, but in certain essentials I am absolutely at variance with some of the conclusions which have been expressed. There is so much to be said, and the time is so limited, that it would be discourteous to the authors and an injustice to myself to attempt to enter into detailed comment, so I shall content myself for the present with only a few remarks.

Briefly, the authors have given an interesting resume of statistical information based almost entirely upon direct-current operation in this country, with some report of results from operation on the three-phase system abroad under conditions differing largely from those characterizing American railroads. They have generalized the features of operation of the steam railroads of the United States, and on that generalization have formulated certain conclusions favorable to the adoption of electricity. All these should receive careful attention and analysis. In addition, they plead for standardization of electric apparatus and equipment, and, if I understand correctly, for a standard of operation based upon the use of single-phase alternating-current motors operated at 11,000 volts and 15 cycles from an overhead trolley.

Their attitude, as expressed in their paper, is emphasized by these two statements:

> The distributing system for altenating-current equipment, which is the only class of equipment deserving serious consideration in connection with the general problem which we are discussing, comprises an addition to permanent way equipment in the form of overhead construction, and electric conductors conveying power from the power house to the trolley or conductor which is carried above the track.
>
> The advantage in favor of electric operation is of course more marked if we assume that alternating-current equipment is to be used, as in general would be the case in the electrification of trunk lines or long divisions.

These are certainly positive affirmations, and if sound would perhaps warrant that spirit of enthusiastic and inquiring prophecy in which the sound basic principles which have made electric traction successful are coupled with various unscientific and quickly discarded proposals, and lightly brushed aside with the query:

> Where, ten years from to-day, will be the 1200-volt or 1500-volt direct-current systems which have been suggested as substitutes for high-potential altenating-current systems in heavy electric traction?

I think I see my initials under these specific voltages; and it is right here that I beg to differ from the conclusions expressed by the authors, and venture to correct them. The higher-potential direct-current systems will still be here, just as we have the lower voltages of the past 19 years, no matter what other developments may take place.

I have been guilty, gentlemen, of some "fads and fancies" while a member of this Institute for a time covering the entire practical development of the electric railway, in which I have played some material part; they have been translated into facts. I have ventured a few prophecies; they are now a part of history.

Operation at 1200 to 1500 volts by direct current has not been advanced by me as a "substitute" for high-pressure alternating currents for heavy electric traction, or as the only means available for this purpose; it has been advocated as one practical development along existing lines which under many conditions, and with the present development of the 25-cycle alternating-current motor, offered some possibilities of railroad operation denied to the latter.

I prefer to define my own position rather than to have it determined for me by others. I do not profess to know what the ultimate developments in this art are going to be, nor will I enter into any rivalry in predicting that a specific type of equipment must be universally adopted, for I feel sure that the selection of a system by any road must be largely individual, and determined by its own necessities.

There will be opportunities for alternating-current equipment, and there are many hopeful alternating-current possibilities, but surely these are not the only practicable methods worthy of serious consideration by such trunk-line divisions as may reasonably consider the possibilities of electric operation to-day.

As useful as a mass of statistics may be, I do not think it necessary, to come to specific conclusions in the matter of electric railway equipment, to generalize all the railroads of the United States. There are a lot of them in the hands of receivers, and some of the others ought to be. They could not be taken out of their hands if they were electrified, and could not raise the money to be electrified if they wanted to. I prefer to deal with the living, immediate questions. There will in the near future be three great trunk-line railroads terminating in New York City, to say nothing of those terminating in Jersey City and elsewhere, on which the question of electric operation is assuming special importance. One of them is proceeding along certain lines, another by somewhat different methods. There has been considerable discussion as to the wisdom of both. I have been guilty of some of the development on one, and I am not ashamed of it. I have somewhat frankly criticized some matters connected with the other, and I have no apologies to offer on that account. But leaving these two roads out of consideration, do we need to look further for a typical trunk-line division than to the third road, the Pennsylvania, from here to Philadelphia? An engine run, and none more typical. I am going to venture, not a prophecy, but a statement. If that line were called upon to be electrified to-day—and it can very properly and seriously consider it—it would not, in my present judgment, be best done by a single-phase overhead trolley alternating-current equipment, whether 25 cycles, 15 cycles, or 1 cycle. There would be a variable half cycle, and it would be the length of time between controller operations. And on many other lines which can properly consider electrification, the higher voltage direct-current system, according to any present development, will give better results than the alternating-current overhead system.

These conclusions are based in part upon a four months' study and analysis of one of the most difficult railroad problems in this country. Had I not been closely occupied in trying to complete that particular investigation, I should be in a better position more fully to discuss the paper of the evening. I hope, however, in the comparatively near future to present to this Institute, of which I have had the honor to be a President, a few comparative statements on the subject of direct-current and alternating-current operation, and I will reserve until that time most of what I have to say.

B. G. Lamme: As the time is limited, I shall confine myself to the question of frequency alone. It may be of interest to consider the changes in frequency from the earliest time to the present, and see what Mr. Stillwell has had to do with such changes. Back in the early times of alternating-current, work, 133 cycles per second was the common frequency. About 1889 or 1890, Mr. Stillwell, in going over the problem, saw that the larger work which was coming called for a lower frequency, and he was one of the strongest advocates in adopting 60 cycles as against 133. A few years later, in connection with the Niagara Falls first large generating station, the question of a still lower frequency came in, and Mr. Stillwell practically made the decision in favor of 25 cycles. At that time it was considered that the development of street railway work, and the use of synchronous converters in such work, was such that it was more economical to use the lower frequency. He now comes forward with 15 cycles for heavy railway work on the basis that the field is going to be large enough to call for a new and more suitable frequency.

It seems to me also, considering the total amount involved in the electrification of the railroads of this country, about $1,500,000,000, that the problem is big enough to call for a frequency which is best suited for the work. The question is whether that should be 25 cycles or something lower. Over four years ago I presented a paper before this Institute, in which I described the Washington, Baltimore and Annapolis single-phase railway, and the frequency given was 16⅔ cycles, a ratio of 2 to 3 to the standard frequency of 25. There were certain reasons for adopting that particular frequency, although 10 per cent. higher or lower would not have been of very great importance as far as the operation of the apparatus was concerned. It was found at the time that there was considerable opposition to the use of lower frequency, principally because most of the projects presented involved existing power plants, or it was necessary to tie the new plant to existing power plants. The projects were also relatively small. Because of commerical conditions, we were practically forced to begin at 25 cycles. However, I still advocated the use of lower frequency when it came to heavier work, as will be found in my discussion of single-phase railway apparatus at the Institute meeting at St. Louis Exposition in September 1904. At that time I said that I considered the heavy railway electrification of sufficient importance to warrant the use of a low frequency which is most suitable for such work, independently of any frequencies already in use. I still hold to that opinion.

The strongest reason which can be given for the lower frequency is the greater output that can be got from a given motor. For instance, with a first-class motor, built for 25 cycles, the operation may be above question, the machine may be considered perfect in every way; but take that same machine and operate it on 15 cycles, and the induction can be raised from 25 to 40 per cent., which means that 25 to 40 per cent. higher voltage can be applied with the same motor-speed, and 25 to 40 per cent. greater output is obtained from the same motor, or 25 to 40 per cent. greater tractive effort can be developed. That in itself is a controlling feature in the question. We have verified it by actual test. For instance, we have taken a 100-h.p.. 25-cycle motor, and obtained from it 125 h.p. at 15 cycles. This motor has good efficiency, good power-factor, and good commutation on both frequencies, at the above ratings. It is therefore not a question whether the 25-cycle motor will work, for it will work successfully, but it is a question how much more can be got out of it by going to the lower frequency. It may be questioned that if 15 cycles is better than 25 cycles, why is not a still lower frequency recommended? The answer is that at 15 cycles the machine is practically saturated, which fixes the output. At still lower frequency there would be a gain in efficiency and power-factor, but not much in output; and there would be loss in other things, such as the speed of turbo-generators and weight of transformers. So there is some point at which a compromise can be made; and it is my opinion, and has been for a long time, that this compromise is considerably below 25 cycles and should be about 15 cycles.

The increased output to be got from a motor at the lower frequency is of advantage principally in getting a smaller number of motors under a locomotive or car, which directly decreases the cost; or, on a locomotive, keeping the same number of motors, there is obtained a bigger output for a given weight of locomotive. But there are some cases where not much is gained by the use of lower frequency; for instance, where it is necessary to operate alternating current-direct current requiring four motors in order to obtain series-parallel control. In most cases we do not get the full gain from the use of 15 cycles for we can not reduce the number of motors. That is one of the conditions met in the New Haven railway equipment, for the direct-current operation on the New York end requires the use of four motors. There are many cases where the power is purchased in which it is necessary to use the higher frequency. Of course, the results are obtained at a somewhat lesser capacity or at increased cost.

There is one point Mr. Stillwell has not touched on, and that is the fact that the single-phase series motor can be made to operate on both 15 and 25 cycles; for instance, a 25-cycle motor will operate beautifully at 15 cycles and at practically the same speed, because the speed has nothing to do with the frequency. A 15-cycle motor, if well designed, will operate on 25 cycles fairly well, at its nominal capacity; at a slightly reduced capacity it will operate very well, so that if a locomotive should be equipped with transformers suitable for operating at 15 cycles, for instance, it could operate on both 25 or 15 cycles. By taking a 25-cycle equipment, nominally designed for 25 cycles, and putting a 15-cycle transformer on it, the equipment is adapted for operation on both 25 and 15 cycles. That is important in connection with the fact that 25 cycles will have to be used in a certain number of cases, but in other cases where the generating conditions can be made suitable, 15 cycles will work to better advantage.

Mr. Stillwell speaks of some of the advantages of the higher frequency, one of which is the better ratio of tractive effort to weight on drivers. We have been making tests at East Pittsburg on some electrical locomotives, at both 15 and 25 cycles, and it is very difficult to determine any difference in the ratio of tractive effort to the weight on the drivers. In some cases the tests are possibly in favor of 15 cycles, in others in favor of 25 cycles; and the difference is probably no more than would be found in making two consecutive tests at any one frequency. If the motors are spring-connected, or have some flexibility between the armature and the driver, which is true in most cases, especially where they are geared, the difference in the tendency to slip practically disappears.

In discussing this question of 15 cycles, we are asked—where is it in use? I will call attention to the fact that quite a number of European companies have adopted 15 cycles for railway work. The Valtellina, plant put in by the Ganz Company, with three-phase motors, uses 15 cycles; and I feel safe in saying that a great deal of the success and good operation of that plant is due to the choice of this frequency. I think they could have made the apparatus a success with 25 cycles, but it would have required much heavier equipment, and with poorer efficiency and power-factor, especially at low speeds. The manufacturers recognized that 15 cycles gave better conditions with the polyphase motors, and adopted it regardless of the fact that that was not a standard frequency in Europe. That system is being extended on the Italian roads.

The Oerlikon Company, of Switzerland, has gone into the single-phase work extensively, with 15 cycles as a standard. The Siemens-Schuckert Company, of Germany, is also manufacturing series railway motors for 15 cycles. The Allgemeine Company, of Berlin, is the principal company which is adhering to 25 cycles, and that is largely due to their type of motor. They have a so-called " series repulsion " motor, in which the characteristics of the motor apparently show to better advantage if the frequency is not too low. It is not directly due to the high frequency that they get better results, but to the fact that the motor should preferably run below the nominal synchronous speed, and this condition is obtained to better advantage by keeping up the frequency.

Bion J. Arnold: On the morning of December 18, 1903, when I arrived in New York from Pittsburg, where I had been examining Mr. Lamme's new single-phase motor and complimenting him on its work. I received a telegram saying that the single-phase locomotive which I had been developing for three years past, and which was at that time ready to make its trial run, had been destroyed by fire. While experimental runs had been made some months before with a rather crude machine, I had everything arranged to make the trial run on the first day of January, 1904, with a new electropneumatic motor which I had developed, and by means of which I expected to demonstrate a single-phase railway in operation. I did not then discover, nor have I yet discovered, the cause of the fire, but it burned up the machine. I felt that unless the machine were rebuilt and an attempt made to operate it, I might be misunderstood by those not familiar with the circumstances. I therefore rebuilt the machine and operated it on August 3, 1904, in time to antedate my competitor in this country by some days. That experiment cost me about $50,000, but thanks to good fortune it cost no other man a dollar.

I believe that by this experiment I was instrumental in advancing the state of the art to such an extent that to-day two or three of our large railroads are being equipped with the single-phase system, invented by others, to be sure, but I believe forwarded by my efforts of some four or five years ago. If my efforts have done that, and I have been instrumental in advancing the art, I am glad I spent the money, as I could not have spent it in any better cause.

I shall not attempt to go into a detailed analysis of the various systems which are involved in the paper, because I think each system has its able champions. It makes no great difference to me personally which system wins, so long as we get a system of electric railroading in this country that will operate the trains for less than it now costs to operate them by steam. I had that idea in mind in starting out on the single-phase experiment, because in 1898 I was engaged in building the Chicago and Milwaukee electric railway, which I believe is considered the pioneer synchronous converter sub-station railroad in the country, possibly in the world; at any rate, the first to be driven by a steam station. I took much risk in that undertaking, risking my personal reputation and my financial resources, in order to demonstrate the success of that enterprise. It was a success, and as you know most of the suburban roads have since been built on those lines.

I make no claim for the invention of many of the devices which entered into the systems. They were invented by some of the gentlemen here present, and by others, and some had just begun to come into commercial use; namely, the synchronous converter, which made the system possible; but I took the risk of putting into practice such a system, took the engineering and financial responsibilities, of making it go. It went. When engaged in that work I felt that that system was not the complete solution of the electric railway problem, because the introduction of the synchronous converter substation necessitated men in the sub-stations, and necessitated more investment than I thought the railroad systems of the country could stand, if they were to be attracted to electrical operation. That started me on the single-phase idea, and as many of you will recollect, we had various discussions on the subject, and it was stated by some of those here present who are now advocating the system, that it could not be done. I maintained it could be done, and had to be done, and it cost me much to find that out. It has been done since by at least two companies in this country, and two or three abroad, and seems to be coming quite rapidly into practice for steam railroad work.

I do not agree entirely with the authors in regard to standardizing this apparatus, as this would shut out the utilization of the talent of the members of this Institute and other societies in this country, and other countries, and the prospect of developing something that may prove better than anything we have now. I am willing to concede, if we are going to use alternating-current railway systems, that we should adopt a standard frequency. So far as my investigation has gone, in conjunction with Mr. Stillwell as a member of the electric traction commission of the Erie railroad, my leaning is toward the 15-cycle frequency. Although I do not want definitely to stand on that conclusion now, I think it is the frequency we will come to on account of the fact that to get the requisite amount of capacity between the wheels of a railroad-car truck, the gauge being limited, it is necessary to get as much power in the space as possible. This can be done by adopting 15-cycle motors, as these motors are more powerful than 25-cycle motors of equal size. It makes the total weight of the locomotive or car practically the same as at 25 cycles, as it increases the size of the transformer. Even then we do not get as much power on the wheels with the alternating-current motor as with the direct-current motor.

I personally believe that some form of high-potential overhead conductor is going to be the final solution of the railroad electrification problem. I believe in the third-rail, where it is applicable, but I do not believe there are many places where it is applicable; in other words, I think that legislation in this country will prohibit the use of the third-rail in exposed places. There are certain types of third-rail which have recently been adopted, which I believe are safer than previous third-rails; I refer to the rail that was devised by Messrs. Wilgus and Sprague and used in the New York Central installation—but I do not think that the use of the third-rail in yards, and under the feet of men, and in other exposed places, will be accepted as the final solution of the problem. In the analysis of the Grand Trunk problem, which I have in charge so far as the engineering decisions are concerned, I chose the alternating-current system, overhead conductor, for tunnel work principally, for the reason that in the large yards at each end of the tunnel, where much switching is done, it seemed essential that the conductor be kept from under the feet of the men. The decision to use the single-phase motor was made some five months prior to the decision by the officials of the New Haven Company to adopt the alternating-current system on their road. The officials of the Grand Trunk did not publish their decision, as certain matters had to go abroad for approval by the English officials before the matter could be publicly announced. but there are men in this room who know that the decision was made at that time.

W. B. Potter: I heartily endorse the recommendation of the authors of this paper as to the desirability of making an effort toward standardizing the essential principles which are involved in the determination of electric railroad problems. To this general proposition may well be added the plea for a uniformity of dimension for such parts of the equipment or general system as might reasonably be made interchangeable.

Considering the matter of standardization in its broader aspect, there does not appear to be any one general system of electrification, in the present state of the art, which engineers would be willing or ought to accept as the standard. For the ordinary city or interurban trolley lines, 600 volts direct current is to-day recognized as a standard. For other classes of work, particularly over long-distance lines with relatively infrequent headway, both the single-phase alternating and the high-voltage direct-current systems possess advantages. The fundamental reasons, however, which have lead to the consideration of a higher voltage trolley may also apply to limit the application of the high-voltage trolley under conditions which can be more economically met by 600-volt apparatus. However much we may desire to limit the number of standard systems we must still recognize that the element of cost, considered broadly, is often the determining factor to be reckoned with. A railroad company could hardly be expected to consider favorably any particular system simply because of general reasons, if the installation of this system involved any considerable additional expenditure on their part.

The matter under discussion this evening, however, relates more particularly to the consideration of the single-phase alternating system than a discussion of the general subject. Of all the apparatus used in the electrification of a railroad, the motor is in particular that part of the equipment which is limited in dimension by the height of the car-body, the clearance over the rails, the width between wheels, and the wheel-base of the trucks. By reason of these limitations, and considering further the proportion of cost which the motors bear to the general expense of electrification, any condition which diminishes the capacity of a motor of given size may very well become subordinate to the motors themselves.

The output of a single-phase motor, particularly its tractive power in the larger sizes, may be limited by the permissible commutation, and as commutation is improved with reduced frequency the suggestion of 15 cycles instead of 25 cycles is worthy of serious consideration. The field of application for the single-phase motor, particularly in the larger sizes which are required for locomotives and heavy railroad operation, will unquestionably be greater if the motors are operated at a lower frequency than 25 cycles.

Compared with a direct-current motor, a 25-cycle motor of corresponding service capacity would weigh approximately 25% more; while at 15 cycles, the single-phase motor would weigh probably not more than 10% in excess of the direct-current motor. The efficiency and power-factor of the single-phase motor on either 25 or 15 cycles would be approximately the same. While the motors and the reactance of line and track are benefited by a lower frequency, there is the increased cost of the generators and transformers to be taken into account.

Messrs. Stillwell and Lamme have both spoken of the effect of a lower frequency upon the maximum available tractive effort. You will appreciate that owing to the characteristics of an alternating current, the average tractive effort of the single-phase motor is approximately 50% of the maximum at the top of the current wave, and with a motor rigidly mounted the wheels would begin to slip at about one half the tractive effort which would be given by a direct-current motor under the same conditions of track and weight on drivers. With the motor mounted on springs in the usual manner, there is introduced some degree of flexibility, and the impulse due to the top of the wave is absorbed by the springs so that the average torque is considerably higher than the theoretical 50%. Under similar conditions of track, with equal weight on drivers and the same method of mounting, tests have been made which indicate that in comparison with the same motor on direct current, the maximum available tractive effort at 25 cycles is from 80% to 90%, and on 15 cycles from 70% to 80%. The maximum available tractive effort is not generally important except in locomotive operation where the maximum draw-bar pull is in a sense the measure of the locomotive's value for starting a train, and during acceleration. On motor cars there is usually an excess of weight on the drivers over that required for acceleration, so that the maximum tractive effort is a matter of less importance.

It is, incidentally, an interesting fact that after the wheels have commenced slipping the direct-current motor shows a much greater reduction in tractive effort than the single-phase motor. The torque being maintained uniformly with a direct-current motor, the wheels rotate rapidly, reducing the coefficient of friction with the rail to something like 20% or 30% of the maximum adhesion. With the alternating-current motor, both on 25 and 15 cycles, although the initial slip is at a lower maximum, the draw-bar pull is only reduced to 80% or 90% of the maximum adhesion. This appears to be due to the fluctuating character of the torque, which at its minimum allows the wheel to secure a slight grip on the rail after the wheel begins to slip. When the wheel is slipping its rotation is not uniform but fluctuates, corresponding with the frequency. While of interest, this higher tractive effort, after the wheels commence to slip, is of little practical value.

Mr. Sprague has referred to higher voltage direct-current motors. With respect to motors suitable for operation on higher voltage direct current and also on 600 volts, I would mention the marked improvement in the motor that has been obtained by the addition of a commutating pole. As an illustration, a motor having commutating poles and designed for operation on 600 volts, can be run at full load on 1000 volts so far as commutation is concerned, and further, such a motor, when the current is momentarily interrupted or there is a momentary rise in voltage, will not flash over, as sometimes happens with motors not having commutating poles. A commutating-pole motor designed for 1200 volts and operated at that potential would be superior to the ordinary 600-volt motor, both with respect to commutation and liability to flash over. I feel that the addition of the commutating pole to the direct-current railway motor, in its effect on commutation, is comparable to the improvement made by the substitution of the carbon brush in place of the copper brush. The carbon brush reduced the sparking and flashing to a permissible degree, and the commutating pole by neutralizing the cause has finally eliminated defective commutation.

A word with regard to the much maligned third-rail. I feel that there is much to be said in its favor. We have not as yet had an equal opportunity to pass judgment on the heavy overhead construction, and I would suggest that we await developments before expressing our opinion too positively with regard to either system of conductors. Both the third-rail and the overhead conductor have a proper field in heavy railroad application; they should be so regarded, and neither of them condemned in the light of our present knowledge.

W. S. Murray: During the year and a half that I have been associated with the New Haven road I have been able to make some rather interesting experiments with steam locomotives, of the freight and passenger types. I thought they might be of interest, particularly in view of Mr. Stillwell's reference to Item 12 of the paper, which relates to "Repairs and Renewals of Locomotives." I understand that this item, for the Valtellina line, represents a figure of 1.8 cents per locomotive-mile. That is a figure I have been very anxious, indeed, to obtain. I have here some accurate figures on the cost of steam locomotive repairs extending over a period of exactly one year, in which ten freight and ten passenger engines were involved. I think you will all be surprised to note what these figures are. I have divided the cost of repairs into two parts; one on the basis of maintenance, the other for purely mechanical or shop repairs, each including labor and material. I have included in the maintenance the following heads: Cost of oil and waste, flues cleaned, ash-pan and grates cleaned, engines wiped, engines turned, engines fired, boilers washed, and the cost of sand. Of course, some of these figures will be matched in electric operation, but to get the actual figure I have included them all.

The record is as follows:

For passenger locomotives: maintenance **$0.0172**; shop repairs **$0.0388**; total repairs per locomotive-mile **$0.056.**

For freight locomotives: maintenance **$0.0142**; shop repairs **$0.0668**; total repairs per locomotive-mile **$0.081.** I believe that these figures give a definite idea of the saving to be effected by the electric method of train propulsion.

I think the most interesting feature of the paper is in regard to the matter of standardization. I hardly think the Interstate Commerce Commission reports are a fair basis to be a determining factor in the establishment of a standard frequency. The Interstate Commerce Commission report includes all the transcontinental lines, and there is no doubt that those lines which have been unassailed yet by electricity could be electrified a great deal cheaper with low-frequency than with high-frequency apparatus, but I do not think that this fact should influence us. I think it is a misleading factor. We must not forget that the electrification of steam railways we are going to consider for the present are to be intimately connected with 25-cycle plants now in operation. It is possible that all of us may see a transcontinental road electrified, but I do not think that that ought to influence us in the determination of a standard frequency, What " may be " should not decide this question but " what is." I think we should remember the fixed charges associated with 25-cycle plants that have not been taken into account in this report, and that the new frequency universally applied would make it necessary to re-equip all these plants operated upon what may now be termed a standard frequency; namely, 25 cycles.

I believe that for power transmission purposes we will all agree that 25 cycles has nearly occupied the position of a standard frequency. Now then, the fixed charges of the properties operated upon a 25-cycle frequency can later be taken care of by a properly provided depreciation figure or sinking-fund, and at the expiration of the depreciation periods we can avail ourselves of the greater data to decide which should be the standard frequency. The gradual interchange of the two frequencies can then be effected without hindrance to operation.

I have not time here to go into the details of this change, but I am sure all of us are agreed that this can be done. I am in favor of having more data and in letting the future consideration of the new data, in connection with the old, decide the proper standard frequency

O. S. Lyford Jr.: This paper is a prophecy. It is interesting to note that the fulfilment of the prophecy has already begun One of the oldest railroads in the country has proved itself the most progressive and has during this present week put into commercial service an electric traction system which embodies most of the features which the authors have assumed as probable characteristics of the standard of the future. Two other roads referred to in the paper have made a start in the direction proposed, but the Erie was the first to arrive. On January 22 the Erie Railroad ran its first electric train into Rochester.

The essential features of the Erie equipment are as follows:

Single-phase railway motors.

Multiple-unit control.

Pantagraph trolley.

Trolley wire supported with steel catenary construction at a height of 22 feet, except under bridges.

Trolley voltage. 11,000.

One sub-station feeding 34 miles of track.

Power received from a power station 90 miles away over a 60,000-volt transmission line.

The conditions are in many ways almost identical with the assumptions made by the authors.

I may say that the operation of the entire equipment was perfect and fully demonstrated the sufficiency and general practicability of the system. On the return trip the Vice-president's private car was hauled as a trailer, resulting in a total weight of train 22 per cent. heavier than that for which the motors were designed. This was on icy, slippery rails.

The impression given by the overhead catenary construction is that it is the adequate thing for heavy railroading. An

11,000-volt trolley wire so supported is a safe proposition. The 11,000-volt wires on the car are so short and so well guarded that they are not a source of increased danger, and all the other wires, housed in the usual way, and operated at only one-half the usual voltage, are unusually safe.

The system in this case is necessarily operated at 25 cycles, as the power comes from one of the Niagara Falls plants which are all built for 25 cycles. The advantage of the lower frequency is apparent, however, Trucks of unusual size are entirely filled with 100-h.p. motors. At 15 cycles, motors of 150 h.p. capacity could be used on the same trucks.

Referring to that part of the paper which relates to comparative costs of operation, more emphasis should be placed on the tabular matter and the deductions made therefrom. The one question is: can steam railroads be operated more economically by electricity? The three items which I presume will be most questioned are Items 12, "Repairs and Renewals of Locomotives;" Item 21, "Engine and Roundhouse Men;" and Item 22, "Fuel for Locomotives," or, in the case of the electric work, the cost of power delivered to the locomotive. I do not propose to discuss these different items in detail, but I would like to point out the fact that they might even be doubled, and still the electrical operation would not cost more than steam. Those of us who have had occasion to study different specific problems have found that the adoption of electric traction, particularly if a high-voltage trolley is used, will not mean an operating cost greater than the cost of steam, and in many cases the saving is considerable. In other words, specific cases which have been investigated, as well as this study of the problem as a whole, show that electric traction is commercially practicable for such lines as can provide for the initial investment. Furthermore, the advantages to be gained by electric traction, due to increased facility of operation and increased loads which can be carried, have not been capitalized in this paper.

The trunk lines of the country are confronted with the problem of more capacity, as has recently been strongly emphasized by Mr. J. J. Hill. There is no doubt but that more traffic can be handled with electric than with steam locomotives, and, at equal cost per locomotive-mile electric traction can be adopted to great advantage by the railroads of this country. On such an occasion as this we should place emphasis on this one important fact and not get into too much discussion of details.

C. L. de Muralt: Mr. Stillwell and Mr. Putnam have covered the questions of comparative energy consumption and comparative operating costs so ably and so fully that there is not much room left for discussion on these points. But on the subject of comparative speed and power characteristics of the various types of locomotives I believe I am in a position to add a few figures which may be of some interest to you. I have had occasion to make an investigation into the hauling capacities of certain locomotives when operating under heavy load conditions. The diagrams compiled during this investigation showed so strikingly the superiority of the electric locomotives over their steam competitors, and, incidentally, also the great superiority of the three-phase aternating-current locomotives over any other type of electric locomotive, that I thought it worth while to elaborate the results somewhat to present them for your consideration.

To make the comparison as broad as possible I have taken what I thought to be the most representative locomotives of their respective classes: the latest direct-current locomotives of the New York Central and Hudson River Railroad, the single-phase alternating-current locomotive of the New York, New Haven and Hartford Railroad, and a European three-phase alternating-current locomotive of the type used by the Italian State Railways. And with these I have compared a Pacific, an Atlantic, and a Consolidation type steam locomotive of recent American Locomotive Company's design—all the steam locomotives being chosen with reference to possessing the greatest possible power; that is, the greatest feasible heating surface, consistent with their weight on drivers.

Detailed descriptions of the mechanical and electrical features of the New York Central direct-current locomotive have appeared in the technical press[1]. So I will simply repeat here some characteristic figures required for the comparison:

Total weight, 95 tons.
Weight on drivers, 68 tons.
Nominal rated horse power, 2200.
Maximum horse power, 3000.
Maximum tractive effort at starting, 34,000 lb.
Three main running speeds:
  a. Four motors in series.
  b. Two groups in parallel, each of two motors in series.
  c. Four motors in parallel.
Normal operating pressure of motors, 600 volts.

On the New York, New Haven and Hartford single-phase alternating-current locomotive, complete data were published last year[2], and I merely extract the following figures:

Total weight, 85 tons.
Weight on drivers, 85 tons.
Nominal rated horse power, 1000.
Horse power in continuous running, 800.
Maximum tractive effort at starting, 42,500 lb.
Speed controlled by voltage variation, motors permanently connected two in series, two in parallel, numerous speed steps.
Normal operating pressure of motors, 235 volts.

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[1] *Street Railway Journal*, November 19, 1904.

[2] *Street Railway Journal*, April 14, 1906.

The three-phase alternating-current locomotive has four driving axles and three motors suspended between them, and the locomotive possesses the following characteristics:

Total weight, 95 tons.
Weight on drivers, 95 tons.
Nominal rated horse power, 2250.
Maximum horse power, about six times nominal full load rating.
Maximum tractive effort at starting, 47,500 lb.
Three main running speeds:
  a. Three motors in cascade connection.
  b. Two motors in cascade connection.
  c. Two motors in parallel.
Normal operating pressure of motors, 3000 volts.

A locomotive of exactly the same type, but slightly lighter, has the following typical dimensions:

Total weight, 85 tons.
Weight on drivers, 85 tons.
Nominal rated horse power, 2000.

I refer to the heavier locomotive as type A, and the lighter one as type B.

Descriptions of the three steam locomotives will be found in the American Locomotive Company's publication. The principal features of the Pacific type locomotive (No. 1212, of the Southern Railway) are as follows:

Total weight including tender,	175	tons.
Total weight of engine alone,	109	"
Weight on drivers,	67	"
Cylinder diameter,	22	inches.
Stroke of piston,	28	"
Diameter of drivers,	72.5	"
Total heating surface,	3895	sq. ft.
Maximum sustained horse power,	1640	
Maximum tractive effort at starting,	33,500	lb.

The Atlantic type of locomotive (No. 3000, of the New York Central and Hudson River Railroad) has the following characteristics:

Total weight including tender,	161	tons.
Total weight engine alone,	100	"
Weight on drivers,	55	"
Cylinder diameters,	15½ and 25	in.
Stroke of piston,	26	"
Diameter of drivers,	79	"
Total heating surface,	3445	sq. ft.
Maximum sustained horse power,	1360	
Maximum tractive effort at starting,	27,500	lb.

And, the Consolidation type locomotive (No. 221, of the Delaware and Hudson Railway) may be briefly described as follows:

Total weight including tender,	164	tons.
Total weight engine alone,	96.5	"
Weight on drivers,	85	"
Cylinder diameter,	21	in.
Stroke of piston,	30	"
Diameter of drivers,	57	"
Total heating surface,	3408	sq. ft.
Maximum sustained horse power,	1020	
Maximum tractive effort at starting,	42 500	lb.

All of these locomotives have a maximum speed of about 70 miles per hour except the Consolidation, the maximum speed of which is about 40 to 45 miles per hour.

The running characteristics, expressed in the shape of tractive effort, speed curves, of all of these locomotives are indicated in Fig. 1.

All of these curves start at a point corresponding to the maximum tractive effort which is obtainable by the full use of the adhesive weight of the locomotive, just below the point where the wheels begin to slip. This maximum tractive effort, dependent only on the adhesive weight, can for each locomotive be counted upon up to a certain well determined speed. Beyond that point, clearly shown in the curves, the maximum tractive effort is independent of the adhesive weight and dependent on the maximum power which the locomotive can develop. And it is from this point that the various locomotives show marked differences in behavior.

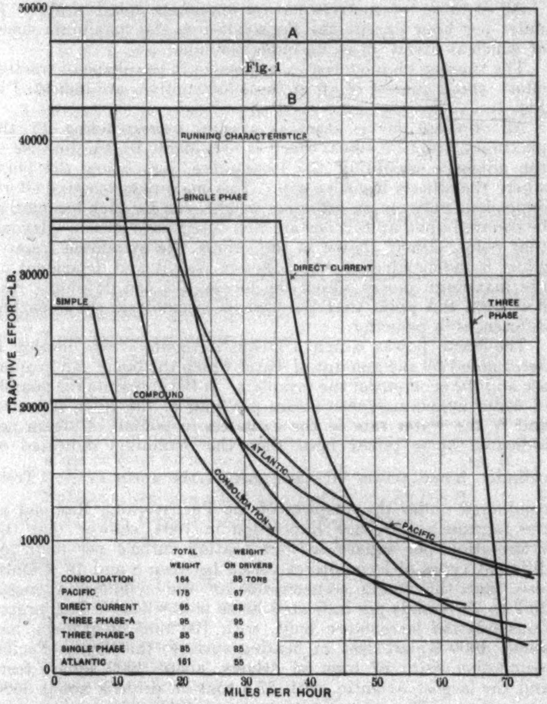
The horse power which a steam locomotive can develop is determined by the amount of water which the boiler can evaporate and the economy of the cylinders. If W represents the pounds of water evaporated into steam per hour at the given pressure, and N the water rate of the cylinders in pounds of steam per indicated horse power hour, then the maximum indicated or cylinder horse power in this part of the curve is $\frac{W}{N}$. Tests conducted under the auspices of the Pennsylvania Railroad at the Louisiana Purchase Exposition in 1904, showed that the evaporation per square foot of heating surface per hour for different types of locomotives varied between 8 and 16 pounds, also that the steam consumption of the cylinders averages 23.7 to 29 pounds per indicated horse power-hour. The largest Consolidation locomotive built, with 100 tons on drivers, has about 4000 square feet of heating surface; the largest Pacific locomotive, with 67 tons on drivers, about 3900 square feet; and the largest Atlantic, with 57.5 tons on drivers, about 3600 square feet. The average evaporation and the average economy under service, not test, conditions, is approximately 12 pounds per square foot of heating surface per hour, and 27 pounds per indicated horse power-hour, respectively. For one horse power developed in the cylinders there must thus be 2.25 square feet of heating surface in the boiler, or:

Cylinder horse power = 0.43 × heating surface in square feet and:

$$\text{Tractive effort} = \frac{375 \times \text{cylinder horse power}}{\text{speed in miles per hour,}} \text{—frictional}$$

tractive effort =

$$\frac{161 \times \text{heating surface in square feet}}{\text{speed in miles per hour}} \text{—frictional tractive effort.}$$



	TOTAL WEIGHT	WEIGHT ON DRIVERS
CONSOLIDATION	164	85 TONS
PACIFIC	175	67
DIRECT CURRENT	95	68
THREE PHASE-A	95	95
THREE PHASE-B	85	85
SINGLE PHASE	85	85
ATLANTIC	161	55

FIG. 1.

The machine efficiency varies in different types, over the range of speeds, from about 74% to 93%. The mean effective pressure corresponding to frictional loss is very nearly constant for all speeds and cut-offs, and averages 3.8 pounds per square inch. The maximum tractive effort, therefore, is given by the relation:

$$\text{Tractive effort} = \frac{161 \times \text{heating surface in sq. ft.}}{\text{speed in miles per hour,}} - \frac{3.8\, d^2 L}{D}$$

where d is diameter of cylinder in inches, L the length of stroke in feet, and D the diameter of driver in feet. This formula, developed by Professor Goss,[1] for simple engines, has been found to corroborate actual tests with exceedingly good accuracy. The majority of the curve sheets in the Pennsylvania tests referred to, show the calculated and test curves in practical coincidence. The curve of the Atlantic type, four-cylinder balanced compound locomotives, No. 3000 of the New York Central and Hudson River Railroad, was plotted from an actual test made at St. Louis.

The curve obtained from the above equation represents the normal continuous output of the steam locomotive. This continuous output is practically the maximum output, since the overload capacity of the steam locomotive is limited to perhaps 25% for periods not exceeding 5 minutes, on account of the impossibility of forcing the boiler above its normal capacity for extended periods.

Electric locomotives, on the contrary, can sustain overloads of considerably greater magnitude for much longer periods of time, without any difficulty.

The curves of the direct-current and the single-phase alternating-current locomotives are very similar in character to the curves of the steam locomotives. These electric locomotives have motors, with so-called series characteristics, that slow down in speed with any increase in load. The direct-current and the single-phase electric locomotives, in common with the steam locomotive, will therefore reduce their speed when they are called upon to haul an increase in load, either in the shape of a heavier train or when running up-grade.

This feature is clearly shown by the curves in Fig. 1, and it is quite interesting to note that the curves of the steam and electric locomotives cross each other. In other words, the tractive effort of the direct-current and single-phase alternating current locomotives, which is better than that of the steam locomotive at low speeds, actually drops off considerably faster with increasing speed, until it is much worse than that of the steam locomotive at high speeds. In fact, if we consider carefully, the curve of the steam locomotive is the result of practically constant power output, while with the direct-current and single-phase alternating-current locomotive the power output as such diminishes together with the tractive effort.

But the greater advantage of the electric locomotive lies in the fact that it can utilize its weight very much better than can the steam locomotive; and if the actual values of tractive effort taken from the curves are compared with the weights of the corresponding locomotives it will be found that the direct-current and the single-phase alternating-current locomotives are capable at low speeds of exerting a very much greater tractive effort proportional to their weight than can the steam locomotives, and even at high speeds their proportional performance is better than that of the steam locomotive.

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[1] New England Railroad Club, December, 1901.

An additional, and perhaps even more important advantage of these electric locomotives over their steam competitors, lies in the fact that the electric locomotive can readily respond to almost any kind of overload demand. As a matter of fact, a prolonged grade for instance, may seriously decrease the usefulness of a given steam locomotive, due to the impossibility of forcing the latter's boiler for any considerable length of time above rated capacity ,while the electric locomotive will slow down, of course, but will, with the assistance of the power house, carry great overloads for any reasonable length of time.

The three-phase alternating-current locomotive not only accomodates itself to such increased demands on its hauling power, but it does so without any great drop in speed, and automatically adjusts its power to the demand. If at 1500 horse power normal output the motors of a given three-phase locomotive have a 2% slip, then at five times the normal tractive effort the slip will be approximately 10%, and the speed will drop from 68.5 to 63.0 miles per hour. Three-phase induction motors of this size (750 horse power) can be built with a maximum torque of 6 to 7 times full load-torque with very good electric qualities. And, notwithstanding the objection sometimes urged that the design must be very liberal for such service, it remains a fact that the three-phase motor can do what the others cannot do, and its intrinsic lighter weight per horse power, its higher efficiency, its more economical distributed winding, and the absence of the commutator, keep down the cost of the three-phase locomotive within the limits governed by competition.

It goes without saying that this constant-speed variable-power characteristic of the three-phase locomotive need not necessarily be made use of in cases where a decrease in speed is no serious objection, while it may perhaps be desired to keep the power within limits. In such cases the three-phase locomotive can just as well be run at lower speeds for the heavier draw-bar pulls. But it may be well to point out here that the power required; for instance, for a 300-ton train running at about 70 miles per hour on a grade of 0.335%, is the same as that required to accelerate the same train on the level with an initial acceleration of 0.56 miles per hour per second. Inasmuch as the system will be designed for the maximum power demands caused by the heaviest trains accelerating, no additional investment in copper or machinery will be required by this constant-speed, variable-power characteristic of the three-phase locomotive.

Instead of saying that the three-phase locomotive is capable of maintaining practically constant speed under any load, while direct-current and single-phase locomotives will drop in speed with increasing load, the thesis may be reversed and the equally true statement be made that the three-phase locomotive is able to develop a certain given tractive effort from zero clear up to practically maximum speed, while the tractive effort of the direct-current and the single-phase locomotives will fall off seriously with increasing speeds, and at maximum speed is only a fraction of what it was at low speed. The curve of the direct-current locomotive shows, for instance, a drop from more than 3000 horse power at 36 miles per hour to only 960 horse power at 60 miles per hour, and the curve of the single-phase locomotive a drop from about 1540 horse power at 23 miles per hour to only 670 horse power at 60 miles per hour. And this is not a question of liberal design, but an inherent unalterable characteristic of all locomotives using series motors.

These features are brought out very clearly by the curves of Fig. 1, but a few hypothetical examples may go to show just exactly how these characteristics affect the actual hauling of trains.

Let us take a locomotive capable of hauling a 150-ton train, and run it over a given stretch in, say 16 minutes, by the use of a maximum running speed of about 65 miles per hour. Now increase the train-weight to 300 tons. The three-phase locomotive will haul the heavier train over the given stretch as before, in 16 minutes, but the direct-current locomotive or the single-phase alternating-current locomotive will have to drop in speed, and will now take 18 minutes to cover the same distance. A loss of over 10% in time, which loss increases with increasing load.

Or take a line of track with one or more grades. Hauling trains of the same weight, the direct-current locomotive and the single-phase locomotive will, compared with the three-phase locomotive, lose a certain amount of time at each grade, and their total running time will, with the same maximum speed, be necessarily considerably poorer than that of the three-phase locomotive.

Or, take the actual curves of Fig. 1 and send the locomotives over a level line at an average running speed of 60 miles per hour, which corresponds to a schedule speed of about 50 miles per hour with stops about 15 miles apart. We then find the maximum tractive effort for each locomotive, and the maximum trailing load which each can haul (assuming a train resistance of 17 pounds per ton) to be as follows:

	Maximum tractive effort	Weight of locomotive and tender	Trailing train weight
Single phase .	4250 pounds	85 tons	165 tons
Direct current	6000 "	95 "	258 "
Atlantic......	9250 "	161 "	382 "
Pacific.......	9750 "	175 "	398 "
Three-phase	9375 "	95 "	457 "

If we investigate the maximum grade which each locomotive can take with a given train at a given speed we shall find the same order of things. It seems, therefore, entirely fair to draw the broad conclusion that for its weight the three-phase locomotive is by far the most powerful hauling engine extant.

To complete the comparison I have plotted a few curves Figs. 2, 3, and 4) showing the relative accelerations which can be obtained from the various locomotives above referred to and I have endeavored to bring together for this purpose locomotives directly comparable, as much as possible, with reference to their weight characteristics. In Fig. 2, I compare the Pacific type steam locomotive (109 tons, 67 tons on drivers) with the direct-current locomotive (95 tons, 68 tons on drivers) and the heavier of the two three-phase locomotives (95 tons, all on drivers). On Fig. 3 the Atlantic type (100 tons, 55 tons on drivers), a most powerful engine for its weight, is compared with the single-phase locomotive (85 tons, all on drivers) and the lighter three-phase locomotive (85 tons, all on drivers). And on Fig. 4 the Consolidation (96.5 tons, 85 tons on drivers) is compared with the lighter three-phase locomotive (85 tons, all on drivers). These weights are sufficiently close together to permit a fair comparison, but I may point out that to eliminate even these small differences in weight, I have assumed that the electric locomotives would use only such portion of their adhesive weight as corresponds to the adhesive weight of the steam locomotive compared with it.

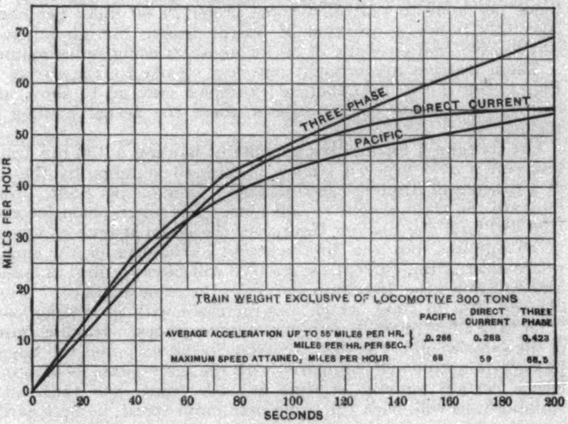

FIG. 2.

This being strictly a comparison of acceleration characteristics, the period of acceleration was assumed to extend to a speed of 55 miles per hour only, so as not to be unfair to those locomotives having a very low rate of acceleration at high speeds.

In Fig. 2 a six-car train, weighing 300 tons exclusive of locomotive, was assumed. The steam locomotive uses its full adhesive weight up to 18.4 miles per hour, accelerating at 0.653 miles per hour per second. From then on the tractive effort drops according to the curve in Fig. 1, and the rate of acceleration correspondingly. A speed of 55 miles per hour is reached after about 200 seconds. The direct-current locomotive accelerates with 875 amperes per motor constant input, 2100 kilowatts maximum, up to 38 miles per hour, from which point on it accelerates on the motor curve at a constantly decreasing rate, until 55 miles per hour is reached, after about 180 seconds. The three-phase locomotive accelerates with a constant input of 2450 kilovolt-amperes, 2200 kilowatts maximum, with three different rates of acceleration corresponding to the three motor connections, reaching 55 miles per hour after about 130 seconds. The energy consumption for the direct-current locomotive and the three-phase locomotive is the same and equal to about 300,000 kilowatt-seconds.

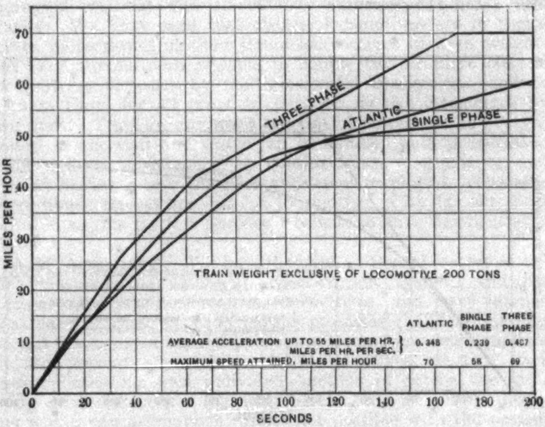

Fig. 3.

In Fig. 3 where the train-weight is assumed to be 200 tons exclusive of locomotive, the steam locomotive again starts with the use of full adhesive weight, and although having at first a low rate of acceleration; it uses its great capacity at higher speeds to full advantage, and reaches 55 miles per hour after about 160 seconds. The single-phase locomotive and the three-phase locomotive start with the same initial input of 2,000 kilovolt-amperes, which, however, gives the three-phase locomotive a better initial tractive effort on account of its better power-factor and efficiency. After 33 miles per hour, the single-phase locomotive accelerates on the motor curve at a constantly diminishing rate of acceleration while the three-phase locomotive utilizes the same initial input up to full speed. A speed of 55 miles per hour is reached by the single-phase locomotive after about 220 seconds, and by the three-phase locomotive after about 115 seconds.

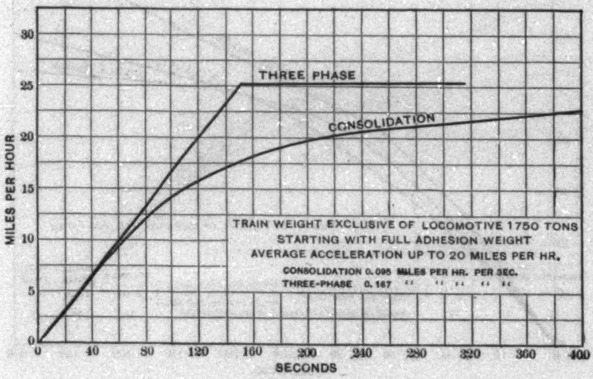

FIG. 4.

In Fig. 4 both the steam locomotive and the three-phase locomotive start with full adhesive weight and accelerate a 1750-ton freight train up to 20 miles per hour at the rate of 0.095 and 0.167 miles per hour per second, respectively, reaching 20 miles per hour after about 200 seconds and about 120 seconds, respectively. By reducing the input for the electric locomotive the acceleration period would be lengthened, but the performance would still excel that of the steam locomotive.

The three-phase locomotive seems, therefore, to be ahead of its competitors also in accelerating qualities, which is quite natural because it is the only one which can utilize a constant input up to full running speed. The three-phase locomotive is mathematically sure of reaching full speed after a certain predetermined time. Locomotives with series characteristics will approach full speed so slowly, that they very frequently do not reach it at all unless the distance between stops is very great.

CONCLUSION

The constantly increasing business on trunk and suburban lines will have as an inevitable result—track congestion. On certain railroads trains are now so heavy, and run at such high speeds, as to tax the capacity of the most powerful steam locomotives to the limit, and the headway between trains is as small as permissible. Here, then, electrification becomes an absolute necessity if the traffic capacity of the lines is to be increased without the tremendous expense of adding new tracks. We have seen that electric locomotives are in themselves more powerful than steam locomotives of even weight; but it is furthermore possible to couple two or more electric locomotives together by multiple-control connections, and to operate them for all practical purposes as one locomotive by one man. Thus an unlimited amount of power can be concentrated in one unit and traffic can be handled both in increased train weights, not limited by considerations of gradients, and also at higher speeds than are at present employed. That the three-phase alternating-current locomotive is by far the most suitable engine for this purpose I believe to have demonstrated above.

A. H. Armstrong: We have listened to the advocates of the 600-volt and the 1200-volt direct-current systems and the various alternating-current motor systems, and have learned that each of these types of motors possesses qualifications that permit the construction of an electric locomotive much superior to the present steam locomotive. It strikes me that each speaker uses his own individual method of saying the same thing—that we have in the electric locomotive a piece of apparatus which can accomplish results not possible with the present steam locomotive. We have outgrown the days of a machine having an indicated output under 2,000 horse power, a maintenance charge of eight to ten cents per locomotive-mile under the best conditions of level-track operation, and double this amount when the conditions are adverse; and we have at our disposal a locomotive that gave a maintenance charge of less than one and one-half cents per locomotive-mile during an endurance test of 50,000 miles, a concentrated output of 2200 horse power nominal, and fifty per cent. increase for unlimited periods by using forced ventilation. I believe that with the assets we have in the electric locomotive, the day has come when we can approach large railroad problems with supreme confidence of winning out over steam competition. It is not a case of the type of apparatus to be used, nor is it a question of frequency, as each case must be considered by itself in order to make the best individual showing for the local conditions involved. Ten years from now we will still be disputing over the question of frequency, alternating-current or direct-current operation, types of motors, and control to be used, etc. Looking back on the history of the steam locomotive, the same lack of agreement is apparent, and even to-day there is no standard type of steam locomotive receiving the universal approval of engineers and operators.

It is not necessary at the present time to standardize electric locomotives or systems of electrical distribution, as we have not yet demonstrated the best type of motor and the apparatus best suited to take care of the needs of both heavy and light electric railroading. No standardizing can be attempted without full experimental and operating data, showing without question that a particular type of apparatus is the survival of the fittest. I regret that no such full operating data are in existence to-day; in fact, no locomotive of the single-phase alternating-current or 1200 volts direct-current type is yet operating in commercial service.

The electric motor provides opportunity for doing something that cannot be accomplished by steam, and this is the reason why it has superseded steam power in the past and will continue to replace the steam locomotive in the future. It is not a question of petty economies effected; it is the broader question of increased facilities, increased gross receipts, and increased opportunities for earning money by means of the electric motor that makes it a successful revival of the steam locomotive. This point has been illustrated in the past by the entire elimination of the steam locomotive in urban and short-haul suburban work. It is being demonstrated in the big terminal electrifications now going on in and around New York. The managers of our large western roads are seriously considering the substitution of electricity for steam, based solely upon the fact that their roads are in need of a type of locomotive which can surpass the best performance of the steam locomotive as constructed to-day, or as foreseen in the future. A steam locomotive having a capacity of 500 tons trailing on a two per cent. grade is going to be a thing of the past as soon as full appreciation is paid to the fact that it can be replaced by an electric locomotive capable of hauling increased tonnage at double the speed. In face of such facts it is a matter of detail consideration to discuss the question of frequency and types of motive power when there are not sufficient operating data and experience at our disposal to enable one type of motor and one system of distribution to stand above all others as possessing qualifications demanding its universal adoption, and, hence, its standardization.

N. W. Storer: It seems to me that the whole question of the electrification of steam railroads comes down to one of dollars and cents, and the system that can be operated and installed for the least money will be the one to be adopted. As may be seen, there are many different ideas on the same question. Many engineers are working on designs of electric locomotives to meet the many requirements which are constantly being requested of manufacturing companies. I have worked over them for some time past, and every time a new proposition comes in, the matter of frequency, or alternating-current or direct-current operation must be decided. It is a question whether the problem can be solved by the simple direct-current system, which our friend, the father of electricity, loves so well, or whether we must go to something higher and nobler up with our voltage and up in the air with our trolley. Our experience is that the decision is generally in favor of locomotive of the single-phase type. I have considered the direct-current locomotive, and the three-phase locomotive, prayerfully and carefully, but, it does not seem to me that either one of these is the type of locomotive which will meet the requirements of the railways of this country. The direct-current locomotive as it has been designed certainly will not do it. In speed characteristics, the single-phase locomotive pleases me much better than the three-phase.

The single-phase locomotive seems to offer the greatest possibilities. With it, we can not only operate up to what might be called the normal speed of a locomotive, but far beyond that. High speeds become simply a question of applying higher voltages from the transformer to the terminals of the motor. The same locomotive can be operated just as well at 10, 15, 20, or 25 per cent. above what might be called its normal voltage as the direct-current locomotive can be operated at it normal voltage. The question of commutation in the single-phase motor is not so much one of voltage as one of induction in the field, one of current which the motor is carrying or, in other words, of the tractive effort which it is exerting.

Every time a single-phase motor is designed for heavy work, the question of frequency arises, and it always works out much better for 15 cycles, for this reason: at least 30 per cent. greater output can be got from motors at 15 cycles than from motors of the same size operated at 25 cycles. That means that at the limit there must be 30 per cent. more motors if the motor is to operate on 25 cycles than would be needed on 15 cycles. That not only increases the cost of motors very much, but increases the cost of all mechanical parts, the motor-trucks must be heavier than trail-trucks—the entire equipment must necessarily be heavier.

The question of efficiency alone is bound to influence the matter very largely. The 15-cycle motor approaches closely the efficiency reached by the direct-current motor, and there is so little difference that it can hardly be detected. In power-factor it comes very close to the direct-current motor. It is above 90 per cent. throughout the entire range of loads in most sizes—it is practically unity.

The saving in cost of locomotives which might be effected by using 15 cycles instead of 25 cycles is mentioned in the paper, and I am bound to say that the difference which is shown is entirely inadequate to cover what in our opinion it would be. I should say that the difference would be at least $5,000, rather than $1,000. That makes a difference which seems to me to be overwhelmingly in favor of the 15 cycles; it is due largely to the number of motors.

In regard to the lighting of the cars, I believe that satisfactory lighting can be obtained with 15 cycles, by using a low-voltage lamp having a heavy filament. A lamp designed 15 volts, to operate on a 15-cycle circuit, will give just as good light and as perfect illumination as the ordinary incandescent lamp on a 25-cyle circuit. It will be entirely satisfactory for the lighting of cars. The many other questions which come up in connection with railway installations will of course influence the choice of frequency very largely, but as I said in the beginning, it is simply a matter of dollars and cents that will determine whether 15 cycles or 25 cycles is going to be adopted for railway work.

William McClellan: Having passed through the experience of equipping some cars with single-phase motors and proper multiple-unit control for 11,000 volts, I believe firmly that the solution of the railroad problem is going to be by means of the 11,000-volt system. Perhaps not exactly 11,000 volts, but a high-voltage overhead trolley with a single-phase motor. In spite of the fact that a heavier motor is needed for the power developed; in spite of the fact that the sub-station is separated into pieces carried on the motor-cars making a large amount of ton-miles in the course of a year—as a whole the system provides a better solution for trunk-line electrification than any other in sight at the present time. This is particularly true if engineers can be brought to think that 15 cycles is better than 25. I, for one, after a very careful examination of every argument, feel sure that nothing stands in the way of the standardizing of this frequency.

Although the steam railroads have not standardized as to details, they have standardized so that they can make necessary interchange of equipment. Electrical engineers must do such necessary standardizing at once. Unless this standardizing is done at once there might result one kind of trolley on this road running locomotives of one type, and another type on that road; this condition might not prove serious with electric locomotives, but if cars cannot be exchanged freely it will be impossible to electrify the railroads of the country, particularly on the grand scale suggested in this paper. So, therefore, I certainly agree that it would be advisable and possible to standardize immediately certain features of railroad practice, the height of trolley, the location of the third-rail, and the voltage and frequency at the trolley and third-rail.

In spite of the fact that the two great manufacturing companies in this country have different systems of control, I see no reason why the train-line jumper should not be standardized as to position and number of wires. That would solve a great many problems in itself, particularly if the jumper could also connect a heating and lighting bus-bar at a standard voltage, making thereby one jumper between the cars to be handled in addition to the air-brake connections. The largest jumper I know of has twelve conductors for the train line, and it is probable that this number is a maximum. Any particular system could use as many of these conductors as desirable. Such an arrangement would permit easy interchange of Pullmans, express cars, mail cars, fast-freight cars, etc., which might have to be used as trailers in multiple-unit trains of different systems.

The above features include all necessary standardization. This, I believe, is the only standardization that is possible or ought to be allowed at present, because anything else would stifle proper advance in the art.

The firm with which I am associated has always found it difficult to derive useful data from published information on costs of locomotive operation. Therefore, another scheme was adopted. It was to take several railroad divisions having different kinds of traffic, a division with large passenger traffic, another having large freight traffic, and another having a good mixed traffic, and if possible get costs on these. In this way we hoped to arrive at some general figures which could be relied upon. I am free to say that while we did have some success and did arrive at some results, on the whole they were unsatisfactory. It was difficult to obtain any reliable costs for coal, wood, and water stations; but the results given in the paper for maintenance of way and structures are as nearly correct as can be stated.

When we came to Item 12, all figures were very unreliable. I believe the only useful method is the one Mr. Murray has adopted of watching very carefully certain locomotives in service. One scheme we tried was to assume that we could substract the cost of boiler repairs and leave only engine repairs, and by some process of assumption get a comparison between costs of electric locomotives and steam locomotives. We found a pretty good agreement that boiler repairs were one-sixth of the total repairs of the engine, but we could find no railroad people who would agree in the assumption that an electric locomotive would cost anything less for maintenance than the machine part of a steam locomotive. Assuming the figures are the same, the maintenance on the electric locomotive might then be considered five-sixths of the present cost of the steam locomotive.

I ask you to beware of any figures given on maintenance by European railways, for the reason that labor is cheap in Europe; and secondly, a great deal of care is given to operation, and costs are likely to be very low. Neither can the cost of running a locomotive 50,000 miles, where it has been in the hands of trained electrical engineers, be taken as a comparative figure for a locomotive running day in and day out, put in the roundhouse at intervals, given more or less attention, but most of the time in the hands of a road engineer who may or may not be able to take care of it.

Some very interesting results were obtained in connection with Item 21. In the first place, I am confident that a "deadman controller" is as reliable as a second engineman, and makes his presence wholly unnecessary. In the second place, a very complete study by a prominent steam railroad man at several different roundhouses at which forty to sixty locomotives were handled per day showed a total cost per engine handled of $1.18. This included all operations from the time the engineman dropped his engine until he took it again. It was found that 54 per cent. of this was peculiar to steam, and could be omitted with electric locomotives. How much, however, would have to be added as peculiar to electric locomotives could not be satisfactorily estimated.

Forsaking figures, there are broad lines on which we may approach any railroad electrification problem and hope to solve it. These are:

1. The flexibility of motor equipment permitting multiple-unit operation for passenger and freight service in a variety of ways.

2. The possible increase in road-miles per locomotive on account of decreased time in roundhouse, etc. An average steam locomotive, making perhaps 3,000 miles per month in freight service, is about 45% of its time on the road, 30% in the roundhouse, and 25% in the yard awaiting orders, etc.

3. The possibility of generating power cheaply by locating the power plants close to coal mines, which will avoid hauling of the coal, and also by making use of large number of small water powers which, if properly developed, amount to a great asset for the railroad; water powers which would be of little use to an individual, but might be of great use to the railroad because its load is distributed over a large territory.

W. I. Slichter: I have been particularly interested in that part of the paper relating to the choice of frequency for single-phase railway work. I have studied the subject for some time and believe there is no question but that a lower frequency is very desirable for the single-phase motor.

There seems to be a unanimous opinion that the output of the motor may be increased some 30 or 35 per cent. by a decrease in frequency from 25 to 15 cycles. In many cases this will make it possible to build in the limited space available on the trucks of a car, a motor of sufficient power to perform the service required, whereas at 25 cycles it would be impossible to obtain sufficient power. But as Mr. Stillwell has pointed out, we must consider how much this change will cost. The other parts of the system, except the transmission line, are more expensive at the lower frequency.

The generator itself may be increased in cost anywhere from 15 to 50%, depending on the size and design. This is due to the fact that a speed corresponding to 15 cycles will be difficult to obtain in turbines, while for slow-speed engine-driven units there will be no great difficulties.

Transformers are increased in cost about 20% by the change, while the distributing system will be decreased about 10% in cost.

Considering, first, an interurban road in which the amount of motive power is small compared with that considered for a large steam road as discussed by Messrs. Stillwell and Putnam, the relative costs of the various parts of an installation are fairly represented as follows:

	25 cycles	15 cycles
Generating station........	34.4%	38 %
Sub-stations..............	1.8%	2.1%
Low-tension construction..	14.8%	14.8%
Low-tension copper........	12. %	11. %
High-tension line.........	5.4%	5.4%
Bonding...................	7. %	7. %
Equipments and cars......	24.6%	23. %
	100 %	101.3%

For this interurban road then a 15-cycle installation would be more expensive.

But turning to a road which approximates steam railroad conditions, the cost of the equipment forms a much larger proportion of the total cost, while the increase in the cost of the power station is not so great on account of the larger size of the units. This transfers the balance to the other side and the figures are similar to those given in the paper. This shows that as we approach heavy railroad work the greater will be the need for the lower frequency.

It has not been pointed out, however, that although the rated (one hour) output of the motor is increased some 35 per cent. by the change in frequency, this is only the output during acceleration, whereas the continuous output rating of the motor is not changed accordingly. For passenger service with long runs and a small percentage of acceleration, not as much is to be gained by the use of the lower frequency.

J. B. Whitehead: As I have listened to the discussion, a certain aspect of the question has suggested itself, and I venture to bring it forward. In considering an electrically propelled vehicle, I take it we may consider that vehicle best which possesses two characteristics to the greatest degree, other things being equal; and these characteristics are the degree to which the vehicle is self-contained and the greatest power that can be got into the space given to the motors. In speaking of the degree to which an electrically propelled vehicle is self-contained, I wish to draw attention to the fact that we may consider an electric locomotive or car more self-contained so far as it requires less attention from the outside. That is to say, the greater the distance between sub-stations and the less complicated the apparatus at the sub-stations, the better. In these respects the alternating-current has the advantages of the direct-current. If the advocates of the direct-current system, could bring forward apparatus that would operate and transmit at the same voltages that the alternating-current system does, a great deal of this discussion would not have taken place. From the standpoint of self-containment, I think that we must look for something from the direct-current side before we yield the position taken by the advocates of the alternating-current system.

It has been very interesting to hear the comments on the other aspect, the greater power which can be got into the space available for motors by reducing the frequency. If 15 cycles is the point at which the advantage of an increase of power within this space stops, being offset by the greater weight and greater cost of transformers, and the difficulties in the generating apparatus, then that is the frequency that will finally be adopted.

The problem is to do the right thing in the right way; and if we can stretch out more and more the distances between the points where the motor needs help from outside by using the alternating-current system, then the alternating-current system will prevail. The footnote suggests a danger from the rising potential of a broken bond, in the case of high-potential operation. I ask if there is any instance on record where there have been unpleasant results attendant upon a broken bond?

L. B. Stillwell: First, I shall reply to Mr. Whitehead's question. We have assumed in our estimate a No. 4/0 conductor in the track circuit in order to aviod the possibility of a dangerous potential on the track in case of broken bonds. My attention has never been called to any case in which danger has occurred from this cause, but it appears to me a theoretical possibility and we desire to make our estimates eminently fair to the steam side of this proposition.

I have been greatly gratified by the discussion on this paper, and I hope that members of the Institute who have additional concrete facts bearing upon the important question of frequency will contribute these facts by letter.

It is evident that the great majority of engineers present would admit that the question of frequency is settled decisively by the testimony we have had in favor of 15 cycles. The testimony of Mr. Lamme, the inventor of the single-phase motor; of Mr. Storer; of Mr. Slichter, and other men who have been active in their development and practical application, to my mind is conclusive as regards the performance of the motor, and they have testified that the difference in favor of 15 cycles, as measured at the draw-bar, is approximately one-third. When this fact is taken into consideration, in view of the general perspective of the problem, which we have endeavored to establish by considering the electrification of our railroads as a whole, it seems to me there is only one conclusion to draw.

In our estimates we calculated that the expenditure for electrical equipment of rolling stock, if the 25-cycle system were used, would approximate $450,000,000. Mr. Storer has stated that the difference in favor of 15 cycles would be at least $5,000 per locomotive, but his figure for the entire locomotive is considerably higher than that which we have assumed in our estimates, and therefore we may scale this $5,000 down to about $4,000. Applying this to 24,000 locomotives, the difference in favor of 15 cycles is $96,000,000, which is ten times the difference in cost of the power-house equipment which is adversely affected by a reduction of frequency.

I believe that to-day we are able wisely to standardize frequency as well as the position of the overload trolley. These things certainly should be agreed upon. The steam roads have standardized everything essential to the interchange of their rolling stock. We must follow that precedent or we shall get involved in all sorts of trouble.

Mr. Sprague is in favor of the direct-current system. He has done so much in the development and application of electric apparatus for traction purposes, first by the direct-current motor and more recently by the multiple-unit system of control, that I should be very sorry to see him make a serious mistake, and I hope that before he nails his flag to the 1500-volt direct-current masthead he will take into account all the evidence presented to-night.

Frank J. Sprague (by letter): Commenting briefly on some statements made by various speakers, which in one breath describe the perfection of results attained by 25-cycle motors and yet complain of their lack of capacity, I am reminded of a sign which I often see in the Subway cars: "We could not improve the powder, so we improved the box."

My criticism of the 25-cycle motor, which has been so well exploited, has not been because of the potential at which a trolley line must be operated. The relations of potential to size of conductor are really of such common knowledge in the primer classes of electrical engineering that it is hardly worth while to discuss that particular feature. Obviously, if alternating currents are to be used then just as high potentials as the physical facts will permit should be adopted, and there is nothing revolutionary in the use of 11,000 instead of 3,000 volts.

Capacity is the keynote of an equipment, and capacity is not measured alone by that of conductors, but ultimately also by motor equipments; and the entire testimony of this evening bears out my criticism, that the 25-cycle motor as constructed to-day does not under like conditions approach the capacity of the direct-current motor. It is proposed to increase this capacity of lowering the frequency. This, also, in itself is not a novel proposition, for it has been discussed for a number of years. It involves a good many questions, some of them going back to the central station. It may be advisable in the end to adopt for alternating-current operation this periodicity, and I ventured months ago to predict that the largest 25-cycle railroad enterprise now carried on would adopt a lower frequency.

In view of the fact that reduction of frequency, which brings a motor more nearly to direct-current conditions, is now acknowledged and advocated as an essential, I find some difficulty in reconciling myself to that subtle reasoning which holds that because a motor is to be run on a part of its route from direct-current supply it is better that it should be designed for the higher frequency.

While in entire sympathy with every practical development, I care not by what means or along what lines, I have opposed, and will continue to oppose any basis of camparison which assumes as worthy of the fullest credence any and every claim made for single-phase alternating motors, while denying either the possibility, practicability, or importance of the utmost development along direct-current lines, whether used for overhead or third-rail construction.

During the last 19 years I have advocated many radical developments on the floor of this Institute, with what results the gentlemen present are familiar. Now, rightly or wrongly, my name is particularly identified with efforts toward higher voltage direct-current operation, even with the third-rail. I willingly accept the sponsorship of that development, and in answer to Mr. Arnold venture to assert that, so far as public sentiment or restrictions are concerned, while it is quite possible that the continued introduction of an exposed top-contact third-rail will be condemned, as it ought to be, it is quite as likely that high-voltage overhead lines, often in close proximity to highway bridges and crossings, and in possibly dangerous proximity to the general public at city terminals, will come under the ban as that a well protected under-contact third-rail will do so.

Further, I will take direct issue with Mr. McClellan, and venture to prophesy that third-rail installations will still proceed with a good deal of regularity.

I am quite sure that many of the critics of the direct-current development are not as familiar as they might be with what has been done in this line within the last year or two, especially in commutating-pole construction and gearless motors. The former, one of my early babies, and now a vital feature in single-phase alternating-current motors, has been reduced to practice with direct-current motors with such success that I fully confirm Mr. Potter's statement as to its efficiency. To my personal knowledge, four-pole motors of this type, varying from 40 to

240 h.p., normal hour capacity, will operate, so far as commutation is concerned, at excess voltages of 75 or 100% with entire freedom from all commutator disturbance. This improvement alone is one of the most remarkable in electric motor construction in recent years; and directly dependent upon it is the possibility of a return to my earlier methods of varying speed and torque of a motor by varying the field-magnet strength, a principle now in common use in variable-speed shunt motors, and which is equally applicable to series machines. This addition of a shunt to the series field has an important bearing upon the comparisons made by Mr. Muralt. The series motor is no longer a machine with a fixed curve, but one with a very wide range of speed and torque control.

In connection with the other important developments, it would be unjust to omit mention of that modest engineer, Mr. Batchelder, who, Columbus-like, by one bold stroke created a departure in gearless machines, individual to direct current work, which is of the utmost importance, and which has received its very practical proof and demonstration, much to the surprise of many critics in this Institute, in the locomotives recently built for the New York Central Railroad.

As most of you are aware, these are gearless machines in which the previously accepted axiomatic principle of fixity of relation between field and armature was abandoned, the latter being mounted directly on the axle, and the fields being carried upon, and as an integral part of, the locomotive frame, supported by its springs and hence moving freely, irrespective of the armature. Not only gears, but armature and axle-bearings are all dispensed with, and the acme of simplicity in motor construction reached. If desired, the armatures of course can also be springborne.

It may interest those who have somewhat cynically questioned 1200-volt direct-current operation, to know that the General Electric, the Westinghouse, and the Electro-Dynamic companies have all either taken, or bid for, contracts requiring the use of motors at this potential.

On the matter of standardization, perhaps I can add a few words. To a certain extent some things take care of themselves. The height of a trolley wire is dictated by the necessity of a clear height above a man on a freight car, and is about 22 ft. There can, of course, be considerable variation from this without in any way interfering with actual operation. The location of the third-rail, with center 28.25 in. from the gauge line, and with a working surface from 2.75 in. to 3 in. above the rail, has been practically accepted, as per suggestion sent out a long time ago by Vice-president Wilgus of the New York Central Railroad as chairman of that road's electric commission.

I suppose I ought to feel flattered to see the universal testimony to the benefits of multiple-unit operation; but some of the speakers outdo the parent in love for his child, and have committed themselves to recommendations of an extreme character. Here, too, there is little to be said in the matter of standardization. I settled that nine years ago when I created a train line composed of sections carried upon, and terminating in couplers on each car, and joined by reversible jumpers between the cars—all constructed, connected, and located so that cars could be connected up in any required order, number, or sequence, and indifferently as to end-relation; and the master-controllers connected therewith had like characteristics with reference to track movement. One of the essential features of this train line is the relative location of speed- and direction-controlling wires, the former unchanged in any connection, and the latter reversed in connection when cars are reversed. Would-be improvers departed from the essential five-wire system, abandoned automatic control, and introduced for a time additional individual wires for various rheostatic steps in the speed control, as on the elevated railway in this city; but the progress of events is carrying them all back to the original lines which I laid down. Practical experience, however, leads me to oppose the introduction into a train line of wires for trunk-line connections, heating, lighting, or brake-control.

I am not able to get up any enthusiasm about a proposition to equip the freight cars of the country with train lines. While the control of two distantly placed freight locomotives would at times be useful, it is not vital, nor are there the same reasons which make simultaneous control of motor cars in passenger trains essential.

Certainly no train operation would be conducted without competent men on locomotives which are distantly removed from each other. Moreover, in view of the universal interchange of freight cars, even if the majority of them were equipped with train lines the introduction of a single one without such an equipment would make useless the balance, and the switching necessary to avoid this would be objectionable. The possible advantages of such an equipment are vastly more than offset by the enormous cost.

Calvert Townley (by letter): The tabulation of distributed opertaing costs of steam roads, contrasted with the estimated costs which it is expected will obtain when steam roads shall have been electrified, is interesting, and the conclusions reached are in line with what electrical engineers very generally believe. I am not sanguine that this tabulation will be given material weight by the men whom it is most desirable to convince; namely, the steam railroad operating officials. Such men, as a class, attach, and properly I believe, much greater weight to statistics showing what has been accomplished than to any figures showing what it is expected will be accomplished, no matter how logical these latter figures may be, or with what care and satisfaction to the compiler they may have been prepared. It is also perhaps unfortunate that in the comparison of the operating costs, the authors of the paper should have omitted any figures on fixed charges. Naturally, such charges, resulting as they would from investments needed to electrify, will increase the total expenditures under electric operation, and will act to offset in varying degrees the estimated savings which Messrs. Stillwell and Putnam have taken. To the man who is unable to estimate what will be the investment required to electrify, this may unfortunately be interpreted to indicate a dread on the part of the electrical engineer that a complete comparison of all expenditures for both methods of traction should be made. There is, furthermore, a deeply rooted feeling that the depreciation in electrical equipment due to the replacement of one type by another, so-called amortization, is much higher than is the case with steam equipment, and there is only one way by which such conviction is likely to be removed; that is, by the actual demonstration in practice that the amount chargeable to amortization is small.

With the principle enunciated by Messrs. Stillwell and Putnam on standardization, I am thoroughly and heartily in sympathy; but in the words of an engineer with whom I discussed this matter, I believe we should only undertake standardization when we have something to standardize. Standards are artificial only to a limited degree, and no edict of the Institute, or of any other body, can successfully long maintain a so-called standard against something better, or when greater advantages can be obtained by departing from the avowed standard. I cannot but feel that the Institute would lay itself open to serious criticism if it should undertake, for example, to establish a standard frequency for electrically equipped steam railroads, when there is no single electrified steam road in this country operated by single-phase current. Particularly would this be true if they should adopt a standard different from every single-phase trolley road now in operation, or in process of being equipped in this country, and having as a basis for such adopted standard only the calculations and experiments of the engineers of the manufacturing companies, extending over but a short period of time. The best type of equipment for the electrification of steam roads will ultimately prevail; but it will prevail by practical demonstration as to its fitness, and in no other way. I should regard it as far better that a few railroads should spend some extra money in later changing the equipment which they may have adopted, rather than that some important development in the art should be hampered or prevented because of a decision made now on insufficient evidence. If the authors of this paper should now advise their clients to adopt something which later may be found to be one of the "discards from the deck," they would only have taken a chance which other engineers have taken before, are taking to-day, and must continue to take for some time to come.

With respect to the advantage of 15 cycles or any other modification of a standard frequency that may be suggested, the burden of proof obviously lies with those advocating the change; to receive serious consideration, reasons for the change must be weighty and the evidence supporting them fairly conclusive. In the present instance, the arguments advanced in favor of 15 cycles are essentially two: first, the lower frequency permits a lighter and more compact motor; and secondly, the induction in the line and track are reduced. Of these two reasons, the first is advanced as the controlling one. Every other consideration is confessedly adverse. It is, therefore, pertinent to inquire, in fact we must know, to consider the subject intelligently, how much smaller, lighter, and cheaper the lower-frequency motor is to be. In undertaking to procure this information, however, we are at once confronted with embarrassment. There being no 15-cycle equipments in existence in this country it is not surprising that the Westinghouse engineers hesitate definitely to predict what will be their relative weight, cost, etc., when they shall have been constructed to meet the necessary widely varying specifications that will certainly be forthcoming as soon as the electrification of steam roads is fairly under way.

In considering the electrification of the N.Y.N.H.&H.R.R. Co., plans were submitted by the Westinghouse Elec. & Mfg. Company for both 15- and 25-cycle passenger locomotives. designed to perform identically the same service. Here, then, we have a definite statement of the relative characteristics of the two types applied to a concrete case, and carefully worked out. The figures include, moreover, not only a comparison of motors, where the 15-cycle is lighter, but also of the transformers, where the 15-cycle is heavier, and, further, of the other parts of the locomotive, which are affected variously and in different degrees. It was found that the 15-cycle machine had the advantage of 5.2% in weight, about 3% in cost, and was slightly better as to its efficiency and power-factor. I have been told that the specifications in this cases were not such as to permit full advantage to be taken of possible 15-cycle construction, but the specifications imposed absolutely no limitation in this direction that was not fixed by the operating conditions. I am further advised that there have been subsequent improvements in 15-cycle motor design that now warrant better claims for it, and that in consequence the present difference of weight of locomotives may perhaps be nearly 10%, or, in some cases, and under varying conditions favorable to 15 cycles, even more.

If the locomotive weight may be said to average 30% of the total train weight, the use of a locomotive weighing 5.2% more will add 1.56% to the total train-tonnage. Similarly, ten per cent. increase in locomotive weight will add 3% to the total train-tonnage. In freight service the ratio of locomotive weight to train weight being less, the increase in total tonnage due to additional locomotive weight would be correspondingly smaller. These additional weights, while undoubtedly undesirable, could hardly be considered controlling or as constituting a sufficient offset to the serious objections of a change in standards, even if such change were not coupled, as it is, with the attendant disadvantages to power station construction in lighting, and in the use of auxiliaries of all kinds.

The statement that there have been recent improvements in 15-cycle motor design is interesting as an indication that the last word in single-phase motor design has by no means been said; indeed, it would be a most remarkable condition of affairs and decidedly contrary to the history of every other electrical development were it otherwise, whether the motor be designed for 15 cycles or for any other frequency.

In the light of these facts, with our high-priced prosperity labor and a soaring material market, it is obviously dangerous even to attempt to state the difference which we may reasonably expect will obtain between the cost, for example, of motors of two different frequencies when the dust settles. On this account it appears to me impossible seriously to consider or to attach much weight to the comparative-cost figures presented by Messrs. Stillwell and Putnam for the possible future electrification of the entire railway sytems of the United States.

In this connection it may be proper to point out a future possibility that has not been touched upon, but which may prove to be an important factor in the frequency question. An engineer who has been familiar with trolley practice only, and who studies steam railroad electrification for the first time, may be pardoned if he is surprised as the comparatively small amount of power required by the steam, and he is likely to be further astounded, and perhaps appalled, at the high peaks and wide fluctuations in load. These conditions do not make for the economical generation of power, but on the contrary impose an abnormally heavy fixed charge to cover capital sufficient to handle peak loads, and an unduly large operating cost for the additional force necessary to operate a station to handle peak loads, the average output of which station is, however, but a small per cent. of its capacity. It is possible that Messrs. Stillwell and Putnam had this feature before them in suggesting the distribution of power 150 miles in each direction from centrally located power houses. However, I am not able to justify the general adoption of such a plan, either on the score of expense or of reliability, though there may sometime be found a particularly favorable case where power can be generated from steam and economically transmitted this distance. I am confident, however, that a much smaller initial investment will be required, and a considerably lower operating cost will obtain, if smaller stations are installed at much more frequent intervals. I believe that such a plan will be found more economical, even with the reduced load-factor thereby entailed. But the question of load-factor brings me to the future possibility above referred to, which is this: as soon as the railway manager discovers that in order to make cheap power he must make it in larger quantities than his road can use, and that his station must also have a good load-factor, he will utilize his good railroad credit in the direction of establishing larger power plants than he himself needs, and he will sell quantities of cheap power to neighboring industries, thereby affording them the advantage of such power at lower rates than they could themselves produce it, and securing for himself, not only cheap power for his own use, but a profit on the sale of the surplus.

Twenty-five cycles is a standard and a satisfactory frequency for induction motors in industrial establishments and for synchronous converters where direct-current trolley systems are in operation. Fifteen cycles is likewise applicable to such service but is concededly not so good, and it is not at present a standard. Should it become so, the cost of transformers for use with it will be materially greater than the cost of transformers for 25 cycles—perhaps somewhat in the neighborhood of 40% more, and the frequency is not one that affords as great a flexibility in the speeds of the induction motors supplied by it.

In the light of the foregoing, the following seem to me clear:

1. That it would be wrong to undertake to establish a standard frequency for single-phase railway operation at the present time.

2. That even after it has been credited with all the estimated advantages claimed for it, a 15-cycle frequency has not yet made out a case entitling it to general preference.

Ralph D. Mershon (by letter): It seems to me that we should go slowly in the matter of adopting a standard frequency for traction work. The reasons for caution in this matter are pretty well set forth in the paper, but there is one of the considerations touched upon which will, I believe, before long have considerably more weight than at present. This consideration is that of the use of induction motors for traction purposes, especially motors whose speed characteristics may be varied by a change in the number of poles, In the case of such method of speed-control, a higher frequency than 15 cycles is desirable as giving greater flexibility in the range of speed. It seems to me it would be much better to wait until the lines of development of traction work are more clearly defined than at present before adopting as standard a frequency lower than 25 cycles.

H. M. Brinckerhoff (by letter): The wide field covered by this timely paper and the broad lines on which the authors have laid out their general argument deserves a much more careful analysis and discussion than was possible at the meeting at which it was presented. A brief written contribution, giving some additional data upon some points contained in the paper or referred to in the verbal discussion may therefore not be out of place.

The first of the four points enumerated by the authors; that is, " the record of certain facts relative to heavy electric traction which have been established by experience " brought out in the discussion various references to one of the items that might be further elaborated upon.

The record of the results obtained on the Manhattan Elevated. Subway, and various interurban railways are used as a basis of comparison upon which to estimate operating costs for steam railway electrification. One of the most frequent criticisms offered by steam railway men is that the period of operation of electric installations has been too short to show fully the cost of repairs and renewals, such as are found in similar items in long established steam railroad operation.

The earliest heavy electric railway system is the Metropolitan West Side Elevated Railway in Chicago, which was the first to operate commercially with the third-rail. Starting in April 1895, nearly twelve years ago, it operated with one motor car per train until 1905, then the multiple-unit control was adopted and a second motor car used on four and five car trains, instead of one as previously.

The total cost of operation per car-mile on this road, starting at about $0.075 in 1896-7-8, showed small fluctuations up to 1905, when it was $0.0931, the highest single year being $0.0971 and the average for the ten years $0.0836. Here then we have a system in its tenth year showing a cost per car-mile for all expenses, omitting taxes only, which compares with the steam locomotive operation of the South Side Elevated of Chicago of $0.106, the Lake Street Elevated of $0.1174 and the Manhattan Elevated of New York of $0.1198 per car mile. The increase noted for electric operation on the Metropolitan from 1895 to 1905 is partly accounted for by considerable increases in rates of wages and cost of fuel and general supplies.

As the writer was connected with this road from the start, and general manager for six years prior to 1906, he states on his personal knowledge that the tenth-year costs included renewals in all the items—ties, rails, frogs, and switches, repainting cars, renewals of armatures, commutators, gears, pinions, and all the various items that might be said to have a considerable first life. The fear very naturally entertained at first, that after a certain period the renewals would become excessive, has not been realized, even after a ten years' term of constant heavy service. The costs are greater the tenth year than the first or second, but are still 25% or 30% below corresponding costs of similar steam locomotive operation. At the same time the service has been immensely improved in speed, frequency, and general desirability.

While it is difficult to compare electric car-mile statistics with steam railway train-mile figures, the facts here noted certainly support the contention of Messrs. Stillwell and Putnam for operating costs at least 20% lower for electric than for steam operation under favorable average conditions.

In using the general average results in the carefully prepared tables of statistics presented by the authors, the danger of applying general averages to specific cases should be clearly pointed out. An average is simply the mean value of two or more amounts, and this average value may vary so greatly from some individual figure on the list from which it is derived as to make a specific application based upon it very misleading. General averages are valuable for general broad considerations, but specific cases must be analyzed and determined upon in their individual conditions.

In their estimates of the costs, the authors have assumed the universal use of single-phase alternating-current apparatus. In the discussion at the meeting it was contended that this assumption was too radical, since no single-phase installation of this character has begun actual service. On the other hand, some speakers criticised the idea and use of the third-rail system as out of date. All past experience shows that a radical innovation is not in itself necessarily bad, neither should an existing successfully operating system, whose limitations have been demonstrated under service conditions, be broadly condemned on these points alone. The present existing heavy electric traction systems are the result of development along a line radically differing from the previous lighter forms of street and other railway apparatus, but this has not prevented the enormous extension of the older lighter form in the field for which it is adapted.

As the writer happened to be engaged upon the design of the original third-rail installation for the Intramural Railway at the Columbian Exposition in Chicago during 1892-3, and joint patentee of the various devices then developed, he feels authorized in saying that no claim was then made that *the only true and correct solution of the electric railway problem* had been evolved. Certain conditions had to be met—a light elevated structure of limited dimensions and clearances, trains of four cars to carry dense passenger traffic, with stations close together, and demands for the highest possible speed and regularity of operation.

This problem was then absolutely new. That the system was evolved, the apparatus designed, installed, and put in operation in less than eight months, and fourteen four-car trains on a line about three miles long, carried successfully from 100,000 to 125,000 passengers in days of 14 to 15 consecutive hours, does not call for any apologies from those connected with this work.

The use of the third-rail itself was brought about by the necessity for collecting large amounts of electric current from a stationary conductor, by apparatus attached to moving cars. The decision to use a large cast-iron shoe sliding on a steel rail was met with many predictions of failure; the result is a matter of history.

The problem met in 1893 is presented to-day, changed only in magnitude. The solution then evolved accomplished its purpose so successfully that in the year 1906 the third-rail system of the U. S. hauled close upon 700,000,000 passengers, at a cost fully 20% below what it would have been with steam.

The writer does not wish to be understood as advocating the whole sale installation of the third-rail on all the steam railway systems of the United States. It has a field, however, of its own which it is occupying successfully. That it has been found to have objectionable features in certain cases is not surprising; on the contrary the variety of conditions which it has successfully met is rather remarkable.

When we discuss the broad problem of electrifying transcontinental railway systems, the added magnitude of the problem involves the further conditions of great distances and large and infrequent train units. The obvious course to pursue under such conditions is to raise the voltage on the working conductor, and that this involves overhead contact is very apparent.

In examining the many forms of alternating-current single- and three-phase lines in Europe last winter, the writer could not but help noting a number of details which are pertinent to this discussion. The use of the relatively high-voltage trolley is successfully accomplished and the insulation of the high-tension-side of the apparatus on the car is not seriously troublesome. It is also true that a system like the Valtellina Line in northern Italy performs all the functions of a steam railway system. Trains of through freight, local freight, express passenger trains, local passenger trains, excursion and specials are run, with interchange of cars and traffic, with the steam railway systems of the country.

There are some points upon which we must be on our guard, however, in making comparisons. Continental railway roadbeds are very superior, as a rule, to the average in America, nor have they the immense and complicated freight-yard layouts and intricate switching problems seen on our lines. The cars are much lower and very light compared with our freight, passenger, and Pullman cars. Wages are much lower and the demand of the public as to quality of service not so severe.

All these must be allowed for in using their cost figures. What they have accomplished in various lines is very instructive and interesting, and it is flattering to know that the incentive vigorously to develop single-phase railway equipments now being pushed by some of the largest firms in Europe came from reports of American effort in this line.

The authors' third point: "Importance of Standardizing Electrical Railway equipment as rapidly as may be consistent with progress" is certainly timely and well taken. Upon the assumption of ultimate universal electrification of the entire railway systems of the country, it is well to note that the interchangeability at present effective on the steam railways does not mean actual identity of apparatus, but sufficient similarity to insure coupling, hauling, heating, and renewal of parts such as journal brasses, etc., upon all lines.

As there is now a variety of types of locomotives on connecting systems and these are operated, generally speaking, on their own lines, so it should be possible to operate through passenger and freight business entirely by standardizing the few items mentioned, and yet retain the advantages of motive power apparatus of different types specially suited to meet certain local conditions.

The great flexibility thus far shown in the development of electric railway apparatus, such as the use of the third rail on private right-of-way and overhead trolley upon streets; and running alternating current on one part and direct current on other parts of a line with the same cars, are only indications of the possible interchangeability of systems of apparently hopelessly divergent characteristics. The two classes, freight and heavy Pullman or passenger cars, are, broadly speaking, the through equipment. On neither of these is it likely to be found desirable or economical to install individual motor equipment and multiple-unit control. The local and suburban trains, with multiple-unit control, will not leave the parent system. Interchangeability then of the *through equipment* does not prevent the selection locally of the most desirable motive power system, provided the present degree of standardization common in steam railway practice is adhered to.

During the present period of development and adjustment of electric traction to steam railroad conditions, the existence and advocacy of different types of apparatus brings to the problem a spirit of emulation and competition that is tending to greater perfection of detail and much more rapid progress than would be the case were all engineers working on a single type. The fact of honest difference of opinion by men striving to meet certain specific conditions successfully is not a sign of weakness as some doubters would have us believe, but a strong argument for the broad applicability of electric power.

A. H. Babcock (by letter): The salient points of the paper seem to me to be the statement that the alternating-current equipment is the only class of equipment deserving serious consideration in connection with the general problem of heavy traction. the question, " where ten years from to-day, will be the 1200-volt of 1500-volt direct-current system? " and the plea for standardization of 15-cycle apparatus.

It is to be regretted that at present there is not available any detailed information covering the actual operating data (such as follows) on the few single-phase roads now in operation. In one of the cases that has come under my personal notice, three passenger cars and two work cars are operated. The passenger cars are equipped with from 100 h.p. motors and weight equipped, but not loaded, 40 tons. The work cars have four h.p. motor equipments and weigh somewhat less. Power is purchased at three phase 60 cycles, is converted to single phase 25 cycles, is metered and paid for at the rate of 1¼ cents on the three-phase side of the converting set. Measured here, the following figures were obtained for one month's operation last fall.

Average tonnage per car operated	36.25
" watt-hours per ton-mile	153
" cost of energy per car-mile	6.92 cents.
" kilowatt-hours per passenger car-mile	6.12
" cost of energy per passenger car-mile	7.65 cents.

It should be noted that the foregoing figures are for power alone, without any fixed charges or other expense. With a total of five cars of all kinds under operation, eight men including the foreman, were needed and employed in the car house on motor-car repairs, with two more men available for emergencies.

Is this sort of thing " the only class of equipment deserving serious consideration in connection with the general problem which we are discussing? "

If this road had been equipped with 1200-volt direct current, under the same operating conditions and losses in transmission as are now made, the energy per ton-mile would have been 107 watt-hours as against the 153 actually recorded, and the monthly cost of energy would have been reduced in proportion.

It is safe to say that the 1200-volt or the 1500-volt direct-current system will be heard of in ten years, if the single-phase system is not developed far beyond the inefficient case cited above.

With reference to standardizing 15 cycles, it may be remembered that the first installation proposed called for 16⅔ cycles. Afterward 25 cycles was made the standard in order to fit existing apparatus, and we were informed that the change in frequency made no difference. Now we are informed with equal positiveness that 15 cycles is to be the panacea, and this in spite of the fact that not one 15-cycle installation is in operation in this country. An engineer responsible for the expenditure of large sums of money may well hesitate about standardizing anything in a field where the very first development has yet to be made and proved.

It is not my intention to appear to condemn the entire single phase system on the showing of the one road the operating costs of which have been investigated by me; nor is the fact that 1200-volt direct-current motors have been specified by me for a large suburban service to be taken as a declaration in favor of high-voltage direct-current as a substitute for single-phase in all cases. The right is reserved to choose for every specific case the type of apparatus best adapted.

All engineers in a similar position must regret the absence of published accurate disinterested information on the operating costs of the few single-phase roads now in operation.

W. S. Murray (by letter): Upon the belief that the two departments in which the greatest economies to be derived in electric versus steam operated trains are fuel and locomotive repairs, it has been my effort during the past eighteen months to secure absolutely reliable data in these two departments of cost concerning the steam operated trains of the New York Division of the New York, New Haven, and Hartford Railroad Company.

FUEL.

Ton-miles are produced in several classes of service, viz:

1. Passenger express.
2. Passenger express-local.
3. Passenger local.
4. Freight.

TABLE 1.—EXPRESS PASSENGER SERVICE.

No. of Locomotive.	Mileage of locomotive in 18 days.	Pounds of coal burned in 18 days.	Average weight of train, including locomotive and passengers.	Total ton-miles of train, including locomotive, passengers, and switching for 18 days.	Total horse-power hours for 18 days of locomotive in revenue service based on average h.p. between Woodlawn and New Haven.	Pounds of coal per indicated h.p.-hour based on average indicated h.p. between Woodlawn and New Haven.	Total revenue ton-miles of train, including passengers and locomotive for 18 days.	Pounds coal per revenue ton-mile.	Pounds coal per indicated h.p.-hour by average ton-mile method.
832	2,782	301,384	573.5	1,556,730	73,100	4.12	1,545,000	0.195	4.40
841	2,336	215,830	480.7	1,123,050	53,150	4.06	1,123,000	0.192	4.34
Avg.	2,559	258,607	527.1	1,339,890	63,125	4.06	1,334,000	0.194	4.37

LOCAL EXPRESS PASSENGER SERVICE.

1262	3,160	295,038	303.0	914,330	63 900	4.62	894.000	0.330	4.54
1258	2,644	264,138	302.2	795,182	57,000	4.64	794,500	0.330	4.54
1272	3,482	353,396	351.5	1,147,520	80,000	4.42	1,114,000	0.317	4.36
1571	1,890	187,180	307.8	577,929	40,600	4.61	566,000	0.331	4.55
1574	1,938	216,583	306.4	593.838	42,500	5.10	593,000	0.366	5.04
Average	2,623	263,267	314.2	805,760	56,800	4.68	792.300	0.335	4.61

An interesting and valuable query is, what fraction of a pound of coal is consumed in producing a ton-mile in any one of the above services? Tables 1 and 2, following, show that it takes 0.169 lb. of coal, 0.194 lb. of coal, and 0.335 lb. of coal to produce a ton-mile in freight, express passenger, and express local passenger service, respectively.

It will be further noted that in the above tables there is given the pounds of coal required per indicated horse power hour for the passenger service. The ten heads under which the compilation of these tables were made show, in order that these data be absolutely reliable, the following conditions must be satisfied:

1. Exact mileages measured.
2. Exact weight of tonnage hauled.
3. Exact weight of coal burned.
4. Maximum continuous number of indicator diagrams taken to determine indicated horse power.
5. A sufficient number of days of continuous test to assure average results.

1. *Exact Mileages Measured.* The zone over which the test was conducted was the New York Division of the N. Y. N. H. & H. R.R. Co. and all trains runs had specified terminals within the zone, the mileages of whch are measured.

2. *Exact Weight of Tonnage Hauled.* The engines, twenty in number, and all cars included in the test were in the regular log of the mechanical superintendent and the superintendent of car service, with measured weights.

TABLE 2.—FREIGHT SERVICE.

No. of Locomotive	Mileage of locomotive in 18 days	Pounds of coal burned in 18 days	Average weight of train, including locomotive	Total ton-miles of train, including locomotive, for 18 days	Pounds of coal per ton-mile
300..........	1,557	230,376	930	1,446,868	0.159
301..........	1,153	184,836	661	761,755	0.242
325..........	1,592	231,366	696	1,108,615	0.209
373..........	2,010	237,006	1,060	2,129,575	0.111
382..........	2,018	304,044	1,240	2,495,072	0.122
386..........	1.274	220,680	731	930,792	0.237
448..........	2.272	413,106	1,255	2,850.046	0.145
453..........	2,350	255,444	872	2,053,142	0.124
Average......	1,778	259,607	931	1,721,983	0.169

3. *Exact Weight of Coal Burned.* Each of the twenty engines coaled from an individual car, the weight of the coal therein being measured immediately before and after the test, the coal cars being placed at the regular coaling points of the locomotives.

4. *Maximum Continuous Number of Indicator Diagrams Taken to Determine Indicated Horse Power.* A continuous set of indicator diagrams were taken on a locomotive for both express and express local runs between Woodlawn and New Haven. A wind-shield was erected over the left cylinder of the locomotive, and the following scheme of indication adopted, viz:

a. One minute allowed for changing cards on steam indicator.

b. Six diagrams per minute to be taken on the same card.

c. Two minutes to be devoted to taking cards.

d. Interval between cards, twenty seconds.

It will be noted that by this method on each indicator card there were obtained twelve indicator diagrams; six for each end of the cylinder. The average mean effective pressure of these cards was taken to secure the indicated horse power for the cycle of three minutes above described. This three-minute cycle of 66% card indication, was practised several days until perfect runs were obtained between Woodlawn and New Haven, east and west. Then five continuous east and west runs were made for both express and express local service, and an average indicated horse power per ton for each class of service was obtained. By this method of continuous indication throughout all parts of the division, both east and west, the results would seem to be accurate.

5. *A Sufficient Number of days of Continuous Test to Secure Accurate Results.* Eighteen days were considered sufficient.

TABLE 3.

	Ton-miles per annum	Tons of coal steam traction	Tons of coal electric traction	Cost of coal steam traction	Cost of coal electric traction	Saving of electric over steam traction
Express...	592,240,000	57,447	29,870	$183,830	$89,620	$94,210
Express loc	348,000,000	58,300	28,600	186,560	85,800	100,760
Express frt	2,223,000,000	187,844	139,010	563,530	417,030	146,500
						$341,470

The test was conducted during the month of August. The track and temperature were favorable to steam locomotive traction.

Table 3 shows the relative amounts of coal required for electric *vs* steam locomotive traction. In the former case the coal as measured in the electric power house; in the latter as measured in the fire-boxes of the locomotives. The cost-item is interesting in this table, indicating that the New York Division when operated by electricity will show a saving by coal alone of $341,470.00 per annum.

It is to be noted that the pounds of coal per indicated horse power hour is not simply the weight of coal used to accomplish an individual engine run, but the weight used in an all-day service of 24 hours, which includes the time the engine is idle. As the engines are indicated for a given revenue run, this weight of coal might be well termed: The pounds of coal per revenue indicated horse power hour.

TABLE IV.—LOCOMOTIVE TEST. PASSENGER AND FREIGHT ENGINES, N

Eng. No.	Year built	Type	Service		Between what points	Locomotive mileage	Labor	Cost repairs		Cost of oil and waste	Total hours service
			Express	Local				Material	Total		
FREIGHT, JAN., '06, MAXIMUM MONTH											
300	1902	K-1-B	East	West	Harlem R. & E. Bridgeport	3225	$31.10	$ 42.24	$ 73.34	$14.30	464
301	1902	K-1-C		Local	Danbury & Dock	1225	15.07	6.04	21.11	5.71	297
306	1902	K-1-C		Local	Harlem River & New Haven	2012	29.00	3366.12	3395.12	13.59	380
325	1900	K-1-B	Extra	Frt.	Harlem River & New Haven	72	740.93	203.69	944.62	6.54	11
373	1903	K-1-B	Exp.		Harlem River & Springfield	3875	33.23	67.75	100.98	14.89	522
382	1903	K-1-B	Exp.		Harlem River & E. Bridgeport	4105	24.82	12.25	37.07	18.17	440
383	1903	K-1-B	Exp. No	Mlk So	Bridgeport & Pittsfield	3314	3.56	6.20	9.76	12.58	[illegible]
386	1903	K-1-B	Ext. Wk	Local	Harlem River & Cedar Hill	2595	120.32	308.07	428.39	13.48	310
448	1905	K-1-B	Exp.		Harlem River & Cedar Hill	4670	35.43	26.32	61.75	14.93	481
453	1905	K-1-B	Exp.		Harlem River & Brookfield Jct.	4754	44.46	33.83	78.29	18.22	376
						29848	1077.92	4072.51	5150.43	127.36	3580
PASS., MAY, 1906, MAXIMUM MONTH											
832	1905	K-4-A	Exp.		New Haven & New York	5145	2.97	19.34	22.31	39.85	416
841	1905	G-4-A	Exp.		New Haven & New York	4410	5.56	37.78	43.34	34.21	310
1210	1900	A-3		Local	Stamford & New York	630	2.37	4.19	6.56	8.21	37
1258	1903	A-1	Wrker	Local	N. H., Stamford & New York	1773	2.40	10.13	12.53	17.39	140
1262	1903	A-1	Exp.	Local	New Haven & New York	4116	6.20	37.63	43.83	18.27	282
1271	1896	A-1	Wrker	Local	Boston, N. London, N. H. & New York	3026	10.78	9.73	20.51	15.64	208
1272	1896	A-1	West	East	New Haven & New York	4976	2.80	4837.03	4839.83	21.05	278
1282	1896	A-1	East	West	New York & New Haven	4191	16.61	38.63	55.24	22.67	188
1571	1893	C-15-A	West	East	Bridgeport & New York	3146	5.16	61.93	67.09	14.21	384
1574	1893	C-15-A	West	East	Bridgeport & New York	3420	0.00	17.77	17.77	12.63	240
						34833	54.85	5074.16	5129.01	192.06	2347
FREIGHT, MAR., 1906, MINIMUM MONTH											
300	1902	K-1-B	Work	Train	Harlem River & Stamford	1806	3.51	.02	3.53	14.35	264
301	1902	K-1-C		Local	Danbury & Dock	1127	1.68	13.82	15.50	3.90	290
306	1902	K-1-B	Way	Frt.	Harlem River & New Haven	1656	0.00	0.83	0.83	6.73	340
325	1900	K-1-B	East	West	Harlem River & E. Bridgeport	1935	31.81	25.50	57.31	15.00	224
373	1903	K-1-B	Extra	Frt.	H. R., E. Hartford & Midway	2403	19.55	16.51	36.06	9.09	294
382	1903	K-1-B	Exp.		H. R. & E. Bridgeport	3053	26.02	18.84	44.86	21.77	284
383	1903	K-1-B	Way	Frt.	Bridgeport & Grt. Barrington	1630	0.00	11.53	11.53	5.07	174
386	1903	K-1-B	Exp.		H. R., C. Hill & Midway	3642	33.83	15.47	49.30	17.14	478
448	1905	K-1-B	Exp.		H. R. & C. Hill	3964	34.62	22.83	57.45	14.11	372
453	1905	K-1-B	Exp.		H. R. & Brookfield Jct.	3768	29.15	46.29	75.44	11.03	371
						24984	180.17	171.64	351.81	118.19	3109
PASS., JULY, 1906, MINIMUM MONTH											
832	1905	G-4-A	Exp.		New Haven & New York	3822	4.49	18.06	22.55	23.83	300
841	1905	G-4-A	Exp.		New Haven & New York	3528	3.78	28.48	32.26	26.11	168
1210	1900	A-3		Local	Stamford & New York	1376	0.00	0.57	0.57	5.72	49
1258	1903	A-1		Local	N. H. & Spfld. N. H. & N. London	3770	2.67	17.43	20.10	14.20	238.50
1262	1903	A-1	Exp.	Local	New Haven & New York	3490	14.61	39.23	53.84	19.84	229
1271	1896	A-1		Local	New Haven & New London	2384	14.73	25.42	40.15	13.18	287.25
1272	1896	A-1	West	East	New Haven & New York	5342	9.30	13.75	23.05	20.15	265
1282	1896	A-1	Exp.		New York & Springfield	3625	3.39	96.11	99.50	13.48	205
1571	1803	C-15-A	West	East	Bridgeport & New York	2499	2.38	50.37	52.75	12.25	270
1574	1893	C-15-A	West	East	Bridgeport & New York	2363	6.06	22.64	28.70	9.47	162
						32199	61.41	312.06	373.47	158.26	2071.75

New York, New Haven & Hartford Railroad Company.

MAXIMUM MONTH

Total No. times flues Cleaned	Cost	Total times ashpan and grates Cleaned	Cost	Total times engine Wiped	Cost	Total times engine Turned	Cost	Total times engine Fired	Cost	Total times boiler Washed	Cost	Total No. of buckets of Sand	Cost
[illegible]	$3.60	55	$8.25	33	$18.15	88	$4.40	1	$0.35	1	$0.54	135	$2.03
[illegible]	3.75	34	5.10	28	15.40	27	1.35	2	0.70	1	0.54	301	4.51
14	2.10	34	5.10	22	12.10	62	3.10	2	0.70	1	0.54	69	1.04
0	0.00	2	0.30	2	1.10	2	0.10	1	0.35	1	0.54	189	2.83
[illegible]	8.40	38	5.70	11	6.05	25	1.25	3	1.05	2	1.08	151	2.27
[illegible]	2.70	57	8.55	50	27.50	114	5.70	1	0.35	1	0.54	189	2.83
[illegible]	0.45	54	8.10	25	13.75	100	5.00	2	0.70	1	0.54	116	1.74
[illegible]	0.75	35	5.25	24	13.20	68	3.40	1	0.35	1	0.54	85	1.28
[illegible]	0.60	61	9.15	33	18.15	118	5.90	1	0.35	1	0.54	200	3.00
[illegible]	1.20	70	10.50	35	19.25	105	5.25	1	0.35	1	0.54	197	2.95
[illegible]	23.55	440	66.00	263	144.65	709	35.45	15	5.25	11	5.94	1632	24.48
[illegible]	5.85	68	10.20	71	39.05	105	5.25	7	2.45	1	0.54	293	4.39
[illegible]	4.35	59	8.85	63	34.65	90	4.50	6	2.10	3	1.62	112	1.68
[illegible]	1.20	16	2.40	8	4.40	8	0.40	1	0.35	1	0.54	34	0.51
[illegible]	2.10	25	3.75	29	15.95	26	1.30	3	1.05	2	1.08	115	1.73
[illegible]	5.55	57	8.55	58	31.90	84	4.20	3	1.05	1	0.54	161	2.41
[illegible]	3.30	39	5.85	32	17.60	90	4.50	2	0.70	1	0.54	136	2.04
[illegible]	9.15	69	10.35	66	36.30	99	4.95	2	0.70	1	0.54	297	4.46
[illegible]	5.40	58	8.70	38	20.90	81	4.05	2	0.70	2	1.08	165	2.47
[illegible]	8.25	55	8.25	51	28.05	88	4.40	14	4.90	2	1.08	244	3.66
61	9.15	61	9.15	61	33.55	92	4.60	2	0.70	2	1.08	312	4.68
[illegible]	54.30	507	76.05	477	262.35	763	38.15	42	14.70	16	8.64	1869	28.03

MINIMUM MONTH

Total No. times flues Cleaned	Cost	Total times ashpan and grates Cleaned	Cost	Total times engine Wiped	Cost	Total times engine Turned	Cost	Total times engine Fired	Cost	Total times boiler Washed	Cost	Total No. of buckets of Sand	Cost
[illegible]	0.45	26	3.90	4	2.20	52	2.60	1	0.35	1	0.54	41	0.62
14	2.10	29	4.35	29	15.95	29	1.45	4	1.40	1	0.54	350	5.25
[illegible]	1.35	29	4.35	12	6.60	52	2.60	2	0.70	1	0.54	75	1.12
[illegible]	0.75	26	3.90	17	9.35	46	2.30	1	0.35	1	0.54	64	0.96
[illegible]	0.90	23	3.45	17	9.35	46	2.30	1	0.35	1	0.54	80	1.20
[illegible]	0.90	25	3.75	28	15.40	83	4.15	1	0.35	1	0.54	190	2.85
[illegible]	0.15	11	1.65	2	1.10	24	1.20	1	0.35	1	0.54	84	1.26
[illegible]	0.15	34	5.10	21	11.55	72	3.60	2	0.70	2	1.08	106	1.59
[illegible]	0.45	56	8.40	28	15.40	112	5.60	1	0.35	1	0.54	186	2.79
[illegible]	0.75	56	8.40	28	15.40	84	4.20	1	0.35	1	0.54	62	0.93
[illegible]	7.95	315	47.25	186	102.30	600	30.00	15	5.25	11	5.94	1238	18.57
[illegible]	4.95	50	7.50	52	28.60	74	3.70	4	1.40	1	0.54	194	2.91
[illegible]	4.20	49	7.35	52	28.60	52	2.60	8	2.80	1	0.54	104	1.56
[illegible]	2.55	17	2.55	17	9.35	18	0.90	2	0.70	1	0.54	65	0.98
[illegible]	4.65	51	7.65	41	22.55	70	3.50	2	0.70	1	0.54	143	2.14
[illegible]	5.55	52	7.80	40	22.00	75	3.75	4	1.40	1	0.54	132	1.98
21	3.15	52	7.80	39	21.45	122	6.10	1	0.35	1	0.54	51	0.77
[illegible]	9.45	76	11.40	66	36.30	96	4.80	2	0.70	1	0.54	244	3.66
[illegible]	5.10	34	5.10	32	17.60	40	2.00	1	0.35	1	0.54	138	2.07
[illegible]	6.45	43	6.45	43	23.65	67	3.35	4	1.40	2	1.08	210	3.15
[illegible]	2.40	17	2.55	14	7.70	36	1.80	4	1.40	2	1.08	87	1.30
[illegible]	48.45	441	66.15	396	217.80	650	32.50	32	11.20	12	6.48	1368	20.52

b. Locomotive Repairs. Table 4 is a typical sheet showing the scheme of accounts kept on each of the twenty locomotives for a period of one year. The sheets selected are those showing the maximum and minimum months for freight and passenger engines.

TABLE 5.

		Mileage made by locomotive	Total cost of repairs in $	Cost of repairs per mile in cents.	Total cost of maintenance in $	Total cost of maintenance per mile in $	Total cost of repairs and maintenance per mile in cents
FREIGHT	Aug. '06	22,342	1323.	5.92	292.	1.31	7.23
	July '06	22,843	1140.	4.99	257.	1.12	6.11
	June '06	26,570	920.	3.46	326.	1.23	4.69
	May '06	32,678	825.	2.52	451.	1.38	3.90
	Apr. '06	22,500	438.	1.95	367.	1.63	3.58
	Mar. '06	24,984	351.	1.40	335.	1.34	2.74
	Feb. '06	24,788	1254.	5.05	353.	1.42	6.47
	Jan. '06	29,848	5150.	17.26	433.	1.45	18.71
	Dec. '05	24,017	2961.	12.33	362.	1.51	13.84
	Nov. '05	29,528	2029.	6.87	455.	1.54	8.41
	Oct. '05	19,523	2050.	10.50	305.	1.56	12.06
	Sept. '05	19,825	1568.	7.91	320.	1.61	9.52
	Total...	299,446	20009.	80.16	4256.	17.10	97.26
	Average per mile...		6.68	6.68	1.42	1.42	8.10
PASSENGER	Aug. '06	32,409	2674.	8.25	638.	1.96	10.21
	July '06	32,199	373.	1.15	561.	1.74	2.89
	June '06	35,272	612.	1.74	583.	1.65	3.39
	May '06	34,833	5129.	14.70	674.	1.93	16.63
	Apr. '06	31,395	429.	1.37	554.	1.77	3.14
	Mar. '06	33,332	743.	2.23	575.	1.72	3.95
	Feb. '06	26,428	1040.	3.93	475.	1.76	5.69
	Jan. '06	37,008	385.	1.04	637.	1.72	2.76
	Dec. '05	31,977	830.	2.63	552.	1.73	4.36
	Nov. '05	43,485	1338.	3.08	681.	1.56	4.64
	Oct. '05	37,394	1172.	3.13	615.	1.65	4.78
	Sept. '05	41,304	1376.	3.33	621.	1.50	4.83
	Total...	417,036	16121.	46.58	7166.	20.69	67.27
	Average per mile...		3.88	3.88	1.72	1.72	5.60

Table 5 is a complete compilation of the twelve months of locomotive repairs and maintenance.

This investigation leads me to the two following conclusions:

1. For a mixed freight and passenger service the same gross draw-bar can be produced by the single-phase method of traction for 60% of the coal required by the steam method of traction.

2. Locomotive repairs are between three and four times as great for steam as for electric locomotives.

L. B. Stillwell and H. S. Putnam (by letter). The paper which we had the honor to present at the two hundred and thirteenth meeting of the American Institute of Electrical Engineers, as stated in its first paragraph, had four objects. 1, To record certain facts relative to heavy electric traction which had been established by experience; 2, to present calculations of relative costs of steam and electric traction in railway service based upon these facts; 3, to point out the transcendent importance of standardizing electric railway traction equipment as rapidly as may be consistent with progress; and 4, to raise the question whether a frequency of 25 cycles per second or 15-cycles per second should be adopted in railway operation by alternating-current motors.

Our purpose in working out and presenting detailed calculations of relative costs of operation by the steam locomotive and the single-phase motor was to secure for ourselves and others a comprehensive view of the great problem which railway engineers to-day are called upon to consider—a comprehensive view being obviously a requisite first step toward an adequate and satisfactory general solution. To realize the magnitude of the problem and the advantages in respect to increased earnings and decreased operating costs which in general will result from the substitution of the motor for the steam locomotive, is to recognize the fact that railways are destined to use electricity upon a scale which demands a general solution and to appreciate the importance of prompt standardization of the frequency chosen for alternating-current work.

While expressing the belief, that as compared with 25-cycles "a frequency of 15-cycles is preferable and should be adopted for heavy electric traction," we stated that our object was rather to present the question of frequency for discussion than to advocate the adoption of any particular frequency, and we suggested a careful consideration of this very important question by the Institute through its Standardization Committee or a special committee.

The oral discussion which followed the presentation of the paper was conclusive, beyond our expectation, as regards frequency. So far as the general practice of engineers who may adopt the single-phase alternating current is concerned, we regard the matter as practically settled by the facts and opinions brought out by the discussion. The designing engineers of both the Westinghouse and General Electric companies testified emphatically to the great increase in power of motors which can be realized by reducing the frequency, and while several speakers questioned the wisdom of now adopting a standard, no one came forward to argue that the higher frequency is preferable.

Mr. Lamme to whom, more than to any other man, we owe the single-phase motor, stated that at 15 cycles the output of a given motor is from 25% to 40% greater than at 25 cycles and that his company had verified this by actual test.

Mr. Storer testified that:

> You can get at least 30% greater output from motors with 15 cycles than with 25 cycles.

Mr. Slichter, the engineer of the General Electric Company, who has immediate charge of the work of designing single-phase motors, said:

> There seems to be a unanimous opinion that the output of the motor may be increased some 30 to 35% by a decrease in frequency from 25 to 15 cycles.

Mr. Potter, chief engineer of the railway department of the General Electric Company, after pointing out some of the difficulties in the way of the adoption of 15 cycles, said:

> I do not think, however, that we can look for the ultimate development of the single-phase motor of 25 cycles.

In his written contribution to the discussion of the paper, Mr. Frank J. Sprague says:

> It may be advisable in the end to adopt for alternating-current operation about this periodicity, and months ago I ventured to predict that the largest 25-cycle railroad enterprise now being installed would adopt a lower frequency.

Mr. Calvert Townley alone, among all who have orally or by written communication discussed the paper, advances arguments in favor of 25 cycles, but even in this case the position taken is one advocating suspension of judgment rather than asserting superiority of 25 cycles, as is shown in the following statement with which he concludes his letter:

> In the light of the foregoing the following seem to me clear:
>
> 1. That it would be wrong to establish a standard frequency for single-phase railway operation at the present time.
>
> 2. That even after it has been credited with all the estimated advantages claimed for it, a 15-cycle frequency has not yet made out a case entitling it to general preference.

The paper and the discussion have established the fact that the increase in cost of the power-house equipment consequent upon the suggested reduction in frequency is far more than offset by the reduction in cost of electric equipment of rolling stock consequent upon the adoption of 15 cycles.

As regards power-house and sub-station cost, we estimated that the difference in favor of the higher frequency is about $10,000,000, assuming that all the American railroads now operated by steam should adopt electricity.

As regards cost of the electric locomotives, Mr. Storer stated that the difference in favor of the lower frequency would approximate $5,000 per locomotive. In naming this figure, doubtless he had in mind the present cost of electric locomotives, while in our estimates we have assumed that this cost, which is now approximately $30,000, will be reduced to $25,000. Making a corresponding reduction in Mr. Storer's estimate, it appears that the saving per locomotive, in the opinion of the chief engineer of the railway department of the Westinghouse Electric & Manufacturing Company, will approximate $4,000 in favor of the lower frequency.

The question whether 24,000 electric locomotives would do the work of approximately twice that number of steam locomotives now owned by the railroad companies is certainly open to discussion. If the actual number required be greater than the number assumed, the argument in favor of the lower frequency is strengthened. In our paper we expressed the opinion that work equivalent to that now done by approximately 48,000 steam locomotives could be performed by electric locomotives numbering from one-half to two-thirds of that figure, and in showing that the change to the lower frequency would effect a saving in first cost of aggregate equipment we used the smaller figure in order to be entirely fair to the higher frequency. Adhering to the figure, 24,000, as representing the aggregate of electric locomotives required, and taking Mr. Storer's figure of $4,000 as representing the difference in cost per locomotive, it appears that while the adoption of the lower frequency would involve an increase of about $10,000,000 in cost of power-house and sub-station equipment, it would save $96,000,000 in cost of rolling stock equipment; both of these figures having reference to equipment of the entire existing railroad systems of the United States. The point made by Mr. Storer, therefore, greatly strengthens the argument in favor of the lower frequency.

The practical unanimity of competent opinion evidenced in respect to the advantages of the lower frequency, and the fact that practically every American designing engineer who has participated actively in the development of single-phase railway apparatus was present and joined in the oral discussion, would seem to have established definitely and finally the wisdom of adopting the lower frequency. It is possible that special cases may arise in which local conditions are sufficient in weight to justify the use of the higher frequency, but it is perfectly clear that hereafter the engineer who in single-phase alternating-current railway work adopts 25 cycles will accept serious responsibility and should be able to base his decisions upon concrete and local factors such as will be found to exist in very few cases.

The fact that the Oerlikon Company, of Switzerland, and the Siemens-Schuckert Company, of Germany, in manufacturing single-phase motors of the type adopted by the Westinghouse and General Electric companies are adopting 15 cycles, is an interesting point presented by Mr. Lamme and is excellent evidence in favor of the lower frequency.

Aside from the interesting discussion of the question of frequency, the paper has resulted in the presentation of certain facts of material value and of numerous opinions, many of which deserve respectful consideration. Among the facts of special value may be mentioned the data presented by Messrs. Lamme and Potter relative to comparative slip of wheels at 15 and 25 cycles. It is highly desirable, however, that these facts be supplemented by further experimental determinations. Mr. W. S. Murray has contributed data of especial value in the shape of costs of steam locomotive operation on the New York, New Haven and Hartford Railroad, these costs being in certain respects analyzed more thoroughly than is usual in the locomotive performance records of our steam railroads. Mr. Slichter's figures showing how the cost of electric equipment in certain cases would be affected by the suggested change in frequency, are of particular interest. Mr. de Muralt's discussion of certain comparative characteristics of single-phase, three-phase and direct-current motors is also of value. It is to be regretted that the comparative merits of the two frequencies under consideration were not discussed from the standpoint of the induction motor. The point was referred to in our paper, and Mr. Ralph D. Mershon in his printed communication expresses the opinion that in the near future this consideration will have greater weight than is now generally recognized. It is certainly desirable to have additional light upon this aspect of the subject, and it is to be hoped that if the advocates of the induction motor for traction purposes have in their possession any facts of importance not yet published they will see their way to present such facts at an early date.

Aside from the discussion of the question of frequency and the presentation of test data, the oral discussion and the written communications subsequently contributed bring out the following facts:

1. That Mr. Frank J. Sprague, and possibly a few other engineers, are inclined to believe that the high-potential direct-current motor, (for example, 1200 or 1500 volts) is perferable to the single-phase motor.

2. That a considerable number of engineers feel that the time to standardize has not yet arrived.

Such advantages as the direct-current motor possesses in the general railway field disappear rapidly when we consider this field as a whole rather than regard special cases in which the reasons for electrification are so weighty as to overcome even the comparative disadvantages of a system apparently limited to 1200 or 1500 volts, and necessarily limited by the interposition of synchronous converters between generators and motors no matter what the ultimate voltage for which direct-current motors may be designed. They also shrink materially when we compare the direct-current motor with the 15-cycle motor instead of the 25-cycle motor.

In the course of the discussion, Mr. Sprague made the following interesting statement:

> I am going to make a prophecy—that on a large number of lines which can by any stretch of imagination be considered as subject to a reasonable prospect of electrification, that 1200 or 1500 volts will on, any present development known, give better results in every way than the alternating-current 15- or 25-cycle overhead system.

It is to be hoped that Mr. Sprague will present facts and figures upon which this interesting prophecy is based. Meantime, however, it may be pointed out that he limits the alleged superiority of the direct-current system to:

> A large number of the lines which can, by any stretch of imagination, be considered as subject to a reasonable prospect of electrification.

The imagination of one man may stretch more than that of another, and in effect Mr. Sprague proposes the plan of special solution. The growth of traffic will constantly operate to bring roads now outside what he considers the practicable field, within that field. Obviously, it will not do to treat this problem as limited to roads having to-day certain density of traffic or limitations of length which may enable the direct-current system to make a good showing. Problems which ten years ago were on the remote horizon are solved and behind us, while problems which twenty years ago were regarded only by the poet are now in the hands of the operating superintendent.

The position which we take in this matter may be stated as follows:

a. A general view of the railway field, including freight as well as passenger traffic, obviously shows that for anything approximating a general solution the single-phase alternating-current system is decidedly superior to the 1200- or 1500-volt direct-current system. This conclusion is corroborated by calculations easily made and based only upon established facts.

b. The admitted advantages of electricity in respect to increased earning power and decreased cost of operation are such as in the near future assure rapid increase in the use of electricity by railway systems now operated by steam.

c. The necessity of standardizing frequency rests practically, although less directly, upon the same arguments as have induced railways to standardize track-gauge, height of draw-bar, location and couplings of air brake, train-line, and steam-line.

In other words, the significance of our estimates of comparative operating costs is that the results, viewed in connection with admitted facts in respect to increased earnings, indicate that a general electrification of important railway divisions, and even of trunk lines, is coming much more rapidly than has been realized, even by electrical engineers; and the lesson to be drawn from this conclusion is that we must standardize as promptly as possible everything essential to convenient interchange of rolling stock.

As regards multiple-unit control equipment, to which Mr. Sprague refers, it will be absolutely necessary to standardize this, at least so far as the train-line connection is concerned, if the time should arrive when freight trains are to be operated by electric locomotives located at intervals throughout the train.

Undoubtedly this possibility now appears remote, by reason of the fact that it would call for a general equipment of the freight cars used by all railways in the United States. It is precisely by this method, however, that the greatest possible advantages of electrification might be obtained. The enormous gain resulting from the ability to operate freight trains of any desired length without increasing the strain on draft-gear, and by a system permitting instant and effective train control at the will of the motorman on the leading locomotive, is obvious to every railway engineer or operator; and it is probable that in no other way could the ability of some of our trunk lines to handle the freight traffic which to-day is overcrowding their existing track facilities be more economically increased. Not many years ago railway operators, in general, regarded the proposition that freight cars be supplied with air-brake equipment as an impracticable dream; to-day the supposed dream is a reality in respect to more than 85 per cent. of this class of rolling-stock equipment. Similarly the idea of equipping all cars with automatic couplers was opposed as impracticable, but to-day such couplers are in general use. In view of these facts, and of the enormously valuable results which might be attained in the case of many trunk lines by employing the multiple-unit system, we contend that the argument in favor of the selection of a standard system of electric supply for railway operation is materially reinforced by the possibility that multiple-unit control may be used in the not very distant future in the operation of freight trains.

It is suprising to find Mr. Armstrong and a few other engineers opposing the idea of standardizing ordinary railway practice. The explanation of their attitude must be found either in the fact that they have inferred more than was intended by our use of the word "standardization," or that they have failed to realize an adequate general view of the railway problem which confronts electrical engineers.

Our paper proposed that standards of practice be agreed upon in respect to: *a*, location of third rail; *b*, location of overhead conductor used with single-phase alternating-current systems; *c*, frequency of alternating traction systems. We remark also that it is clearly desirable but probably less easy to agree upon a standard system of multiple-unit control for train operation.

As reported in the stenographic notes of the discussion, Mr. Armstrong said:

> It is not a case of types of apparatus, or a question of frequency. Each case has to be considered by itself. In ten years from now we will still be disputing over the question of frequency, alternating-current or

direct-current operation. Looking back on the history of the steam locomotive, we have no standard. You can talk to the representatives of the different roads, the master mechanics and different engineers, and they have their own ideas about various matters in connection with their locomotives, * * *

Undoubtedly ten years from now the master mechanics and engineers of electrically operated railroads will still have their own ideas about various matters in connection with their locomotives. As regards all things essential to interchange of rolling stock, however, it is safe to assume that practice will be uniform; and the earlier uniformity is attained, provided that system best fitted to survive is selected, the better for all concerned.

The question whether it be wise or unwise now to agree to set aside as inadequate for the solution of the general railroad problem all direct-current systems, depends upon the question whether we now possess adequate knowledge of the possibilities and limitations of the contrasted systems. It is our contention that such knowledge is now available.

In 1890 the standard frequency of 60 cycles was chosen for lighting purposes. This choice was based upon knowledge certainly not more complete in respect to the requirements of the field of use, and the limitations and possibilities of apparatus applicable thereto, than is now available to enable us to make a wise choice of frequency for railway apparatus. In 1890, 60 cycles was not a case of the survival of the fittest. As a matter of fact, when it was chosen as the standard frequency to supersede the higher frequencies previously in use, it had never been embodied in a commercial plant in actual operation. Nevertheless it appears to have withstood successfully the test of time.

Similarly in 1890 the Westinghouse company selected as standard for work in which synchronous converters were to be employed extensively, the frequency for 30-cycles. About two years later, and before any important plants using 30-cycles had been installed, this was changed to 25-cycles, owing primarily to the fact that the Niagara Falls Power Company had arranged to install turbines operating at 250 rev. per min.—a speed which did not permit the development of 30-cycle current by alternators directly connected to the turbine shafts.

The frequency, 25 cycles, when adopted for the Niagara installation, was not selected as the survival of the fittest among a number of alternative frequencies preferred by various engineers and experimented with in commercial service at the expense of the purchaser. At the time it was chosen, knowledge of the facts essential to a wise choice was far less exact and comprehensive than to-day is our knowledge of the considerations which should enable us to predetermine and select that frequency which is best fitted to survive in railway service.

In his exceptionally valuable contribution to the discussion, Mr. H. M. Brinckerhoff takes the position that the essential condition of interchangeability of through equipment does not prevent the selection, locally, of a variety of motive power systems:

Provided the present degree of standardization common in steam railway practice is adhered to.

The question is very important, and it is a fortunate fact that electric rolling-stock equipment offers many' interesting possibilities of operation over lines supplied with electric motive power of various types. Such operation, however, as illustrated by the equipment of the New York, New Haven and Hartford Railroad, which is adapted not only to the 11,000-volt single-phase overhead system chosen by that company, but also to the direct-current third-rail system of supply used in the Forty-second Street terminal, implies, necessarily, a degree of complication expensive, and, from the operating standpoint, very undesirable.

If some of our railways are to use 6,600-volt overhead trolley systems of supply, others 11,000-volt systems, still others 1,500-volt direct-current systems, 600-volt third-rail systems, and any other systems which ingenuity can suggest, no conceivable complication of rolling stock equipment will permit operation of motive-power units over the railway lines of the country as a whole.

As regards the necessity of standardization in order to avoid confusion and loss as the zones of electrification of our railway systems are extended, the following considerations, not specifically mentioned in the paper or in the discussion, and apparently overlooked by some who have discussed our paper, may be referred to:

1. The effect of consolidations. The doctrine of special treatment of individual cases of electrification now presented to the electrical engineer, if adopted, will lead to needless expense and great inconvenience in operation in cases where properties equipped with different systems may be consolidated at some future date. The same is true in case of a transfer or sale of a section of line by one railroad property to another.

2. In emergency, in case of accidents blocking the line, our steam railways not infrequently send their trains to destinations by using lines belonging to neighboring railways under different management. If one line is to use the 1200-volt direct-current system, and another the alternating-current system, such accommodation will be impossible.

3. At junction points and terminals the use of different systems in permitting interchange of rolling stock is in many cases practically prohibitive. Every terminal in the city of Chicago is in use by two or more trunk-line railways, and in such a case as this obviously uniformity of systems, frequency, etc., is essential.

It appears unnecessary to elucidate further the reasons which from an operating standpoint argue so strongly against the idea of special solutions of individual cases. Every experienced railway man will recognize their force without argument.

It has been suggested that the adoption of a standard system of supply for railway lines may retard progress by limiting, or checking, the spirit of emulation and competition of inventors and engineers. This question, it will be noted, is not raised by our suggestion that the frequency, 15-cycles, be adopted as a standard for alternating-current railway work. Obviously the opportunities for improvement and development are quite as great at 15 cycles as they would be at 25 cycles.

The question is pertinently raised by our expressed opinion, that for a general solution of the broad problem of railway electrification only alternating-current systems are deserving of serious consideration, and those who believe that direct-current systems may be capable of development to a point which will make them, or one of them, effective and satisfactory for the solution of the general problem, are justified in making the point referred to. For ourselves, the arguments in favor of the alternating-current system are such as justify the setting aside of direct-current systems and concentration of effort in the prompt standardization and more rapid development of the alternating-current system, which, by its essential characteristics, is obviously best adapted to the solution of the general problem.

It is pointed out that the existence of a certain number of 25-cycle generating plants, sometimes owned by the railway, and possibly available as a source of power supply for emergencies, is a consideration of weight in some instances. The answer to this is that undoubtedly in each specific case of contemplated electric installation the problem should be carefully studied with reference to local as well as to more general considerations, and it is not impossible that in some cases the weight of local considerations may justify departure from the general standard. This obvious fact, however, does not argue against the general adoption of a standard. So far as it has weight, undoubtedly it argues in favor of 25 cycles, but it in no way supports the position, which some have taken in opposition to our contention, that a standard should be promptly agreed upon.

One or two contributers to the discussion have criticised our use of the *Statistics of Railways*, issued by the Interstate Commerce Commission, on the ground that these reports are not reliable. For our purposes and as used by us they are, on the contrary, entirely adequate and convincing. The fact that they are not complete in detail does not materially affect their value for our purposes, as we are dealing with the ratio of the individual items to the total operating expense. Obviously, the ratio of saving indicated by our calculations cannnot be applied to individual roads indiscriminately. It could be so applied only to a railway which might happen to represent exact average conditions. It is hardly necessary to explain that the management of any railroad contemplating the adoption of electricity must study the problem with reference to its detailed and carefully analyzed conditions and costs of operation. In attempting to fix comparative costs of the various items of operating expenses, moreover, we have used not only the reports of the Interstate Commerce Commission, but the annual published reports of many railroads and also detailed unpublished reports kindly furnished by officials of the Pennsylvania, the Erie, Missouri Pacific, Denver and Rio Grande, and other railroad companies.

One or two critics have considered it unfortunate that, in connection with our calculations of comparative operating costs, we did not include an estimate of the capital charges involved in the case of electric equipment. This omission was deliberate. To include capital charges is in no way essential to the purposes of our paper, and to do so would raise questions tending to divert attention from the object which we had in view. For example, the treatment of the question of " depreciation " is one which might well become the subject of a paper of considerable length, and the methods of financing railroads in America are so far from having attained a standard of practice that we have deemed it best to show only the calculated saving in operating costs per mile of line as compared with interest on the cost of required electric equipment, exclusive of rolling stock.

Several gentlemen who discussed the paper expressed the opinion that, while the apparent reduction in operating costs, as shown by our analysis, is 18% (exclusive, of course, of capital charges), roads in general will not make the change in order to effect this economy, but will be influenced to a much greater extent by the increased earning power resulting from the change. This consideration is not new to the authors. One of them recalls pointing it out to the president of the Manhattan Railway Company some ten years ago.

The results of our estimates, in which we have endeavored to compare the operating expenses under a system of electric traction with the actual grand averages of operating expenses throughout the United States, are more favorable to electric traction than we had anticipated when this work was undertaken, but it is hardly necessary to point out that no competent engineer would infer from these results that every railway in the United States is likely to be electrified in the immediate future. The possible economies effected by such substitution, however, when considered in connection with the increase in earning power to be anticipated, leads to the conclusion that the electrification of our railways is destined to be carried on much more rapidly than is realized to-day by the average engineer, and emphasizes the necessity of prompt standardization of everything essential to convenient exchange of rolling stock.

The communication from Mr. A. H. Babcock is interesting, but has no particular bearing on the general railway problem under consideration. He objects to our expressed opinion that alternating-current equipment is the only class of equipment deserving serious consideration in connection with the general problem of heavy traction. He has found an alternating-current installation comprising three passenger cars and two work cars weighing about 40 tons each. These cars are operated by 25-cycle single-phase current obtained from a 60-cycle source through the interposition of a motor-generator set. The energy is metered and paid for on the three-phase side of this set. The conditions of service are in no way defined, but the limited equipment suggests a very low load-factor and consequently very low efficiency of conversion from 60 cycles to 25 cycles.

Mr. Babcock asserts that if the 1200-volt direct-current system were used the energy per ton-mile would be 30% less. This is easily conceivable, particularly if Mr. Babcock has based his calculations upon the use of synchronous converters in this case as against a motor-generator set as in the other. The case to which he refers is obviously one of ordinary interurban trolley operation, with frequent stops; and in this field many cases of direct-current practice might be adduced in which the energy consumed per ton-mile, owing to special and local conditions, is comparable to that which he has found in this particular instance of alternating current. Obviously, the point which he attempts to make is not one which will materially influence general conclusions in respect to the problem of heavy traction. Mr. Babcock asserts his intention:

> To reserve the right to choose for every specific case the type of apparatus best adapted.

In the interest of the great railway property for which he is retained as electrical engineer, it is to be hoped that he will bestow further consideration upon this very important question of engineering policy. The 1200-volt direct-current system is probably capable of attaining excellent results in a limited field, such as the electrification of a terminal, but generally speaking the system adopted for the electrification of a terminal should be one adapted to future extension to the railway division or even to the trunk line.

The substantial accuracy of the general results of our calculations relative to reduction of operating expense resulting from the substitution of the electric motor for the steam locomotive has not been seriously questioned. Our estimates of the aggregate output and cost of power-house equipment which would be required for the operation of the entire system of the United States rest primarily upon certain stated assumptions as to length of line supply from a given power house, and to this fact some reference has been made in the discussion.

We therefore avail ourselves of the opportunity to supply, in the form of an appendix to our paper, an explanation of methods used in determining power-house output and load-factor, a statement relative to the effect of resistance due to grades, and also a brief statement relative to recuperation.

Clarence Renshaw (by letter): Mr. A. H. Babcock has contributed to the discussion of the Stillwell-Putnam paper by letter. He describes his observations on a visit to a single-phase electric railway. I have been intimately conversant with the operation of this railway through engineering reports from those who have had charge of the installation and initial operation of the apparatus.

Mr. Babcock has neglected to mention a number of facts which materially affect the conclusions which should be drawn from the material which he does give. To overcome certain specific faults in insulation and workmanship, which developed in operation, the motor armatures were rewound. A number of the men whom Mr. Babcock mentions were presumably engaged upon this work, as the normal number which is now employed is very much less.

During the month to which it is presumed Mr. Babcock refers, the total car-mileage of the road was 15,797 miles, including trailers and freight cars. The total motor-car mileage was only 13,009 miles, or approximately 87 miles per car per day. The cars were operated at a schedule of approximately 19.5 miles per hour between terminals, so that the daily mileage of a car represents only about 4.5 hours actual running. Under such circumstances, the load-factor in necessarily very low and the power consumption, on a car-mileage basis, from the 60-cycle circuit, where the power measurements referred to by Mr. Babcock were taken, is necessarily high. This was further accentuated by the fact that, at the time of his visit, polyphase generators which were not well adapted for this service were used for supplying single-phase current. These have since been modified by rewinding them for single-phase operation. Since this modification, one generating set is ordinarily ample for operating the road, whereas two motor-generator sets in parallel were usually required during the month to which Mr. Babcock refers. Consequently, the conversion losses in the sub-station were abnormally high.

Even the figures which are given—153 watt-hours per ton-mile—are not unusual when the load-factor is low. I have a test giving the actual measurements on a road through synchronous converter sub-stations. Three cars of 28 tons operating on this road required 202 watt-hours per ton-mile during the month of January, 1906. This illustrates the high power requirements per ton-mile when there are but few cars and the load-factor is low. A comparison of these two examples shows the marked advantage of single-phase operation under such conditions.

It may be noted that the company operating the road to which Mr. Babcock refers has given a favorable judgment on the operation of the road, as indicated by considerable extension and an increase of more than 100 per cent. in their car equipment.

A paper presented at a meeting of the Schenectady Branch of the American Institute of Electrical Engineers, Schenectady, N.Y., January 31, 1907.

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LINE CONSTANTS AND ABNORMAL VOLTAGES AND CURRENTS IN HIGH-POTENTIAL TRANSMISSIONS

BY ERNST J. BERG

With a large number of the very high voltage transmission systems being planned at present, the information readily available in regard to capacity, inductance, etc., of transmission lines, is not sufficient to pass upon some of the important questions which necessarily will be brought up. Below are given, therefore, the equations from which these constants can be determined.

$$L = \frac{161}{10^3}\left[2\,{}^{n}lg\,\frac{2\,D}{d} + \frac{1}{2}\right]$$

where L is inductance per mile of wire (single phase or three phase) expressed in millihenrys; D is the distance between centre of wires;* d is the diameter of wire in the same unit as D.

The capacity between one wire and neutral, whether single- or three-phase circuit, is

$$C = \frac{890\,k}{10^4\;{}^{n}lg\;\frac{2\,D}{d}} = \frac{386\,k}{10^4\;{}^{10}\log\;\frac{2\,D}{d}}$$

Where C is expressed in microfarads per mile of wire against neutral, D and d in the same units as before. k is the specific inductive capacity, which for air is 1.

Neglecting the quantity ½ inside the parenthesis in the inductance formula, which is permissible if the distance between the wires is large compared with their diameter, we get

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*To be absolutely accurate, D is the distance between the center of one conductor and the surface of the other.

$$L = \frac{742\ {}^{10}\log \frac{2D}{d}}{10^3}$$

$$C = \frac{386\ k}{10^4\ {}^{10}\log \frac{2D}{d}}$$

We see at once that the product of inductance and capacity is constant, regardless of the distance between wires or their diameters, or

$$L\ C = \frac{286}{10^4}$$

where L is expressed in millihenrys, and C in microfarads, both referring to one mile of wire; or

$$L_1\ C_1 = \frac{286}{10^{13}}$$

If L_1 and C_1 are expressed in henrys and farads; therefore, if M = number of miles of wire, we get:

$$L'_1\ C'_1 = \frac{286\ M^2}{10^{13}}$$

where L'_1 and C'_1 are the total inductances and capacities of each wire in the system.

The natural period; that is, the frequency at which the system oscillates due to its own constants, depends only upon the inductance and capacity, as long as the resistance is reasonably low so that oscillation can occur.

With concentrated inductance and capacity, it is expressed as $f = \frac{1}{2\pi\sqrt{L\ C}}$.

With distributed capacity, Steinmetz has shown that the frequency is expressed by $\frac{1}{4\sqrt{L\ C}}$ where L and C are given in henrys and farads.

Since, as shown above, the product $L\,C$ is independent of distances of conductors or their size, it is therefore evident that the natural frequency is also independent of these constants and depends only upon the distance of transmission.

Generally, when discussing the natural frequency of a line, we mean the frequency which the line would have if charged above the ground potential by atmospheric influence, and suddenly relieved of the charge. In this case we should consider the inductance and capacity against ground. These are found by the following equations:

$$L_0 = \frac{2\times 161000\,M}{10^9}\ {}^{n}lg\,\frac{4\,D}{d}$$

$$C_0 = \frac{178000\,M}{2\times {}^{n}lg\,\frac{4\,D}{d}\ 10^{12}}$$

where L_0 and C_0 are given in millihenrys and farads; M is number of miles of wire; D is distance of the conductor above the ground; and d is the diameter of the conductor.

The frequency so obtained is, of course, the same as when using the inductance and capacity between wires. A ready way to determine the natural frequency of the line is to calculate it from the fact that the length of the line constitutes one-quarter of the wave, so that, since the velocity of electrical propagation is the same as that of light, the frequency, for instance, for a line 150 miles long, is

$$\frac{187000}{4\times 150} = 312 \text{ cycles.}$$

It is, of course, important that the fundamental frequency, or that of any prominent harmonic, shall not be the same as the natural period of the line, since, when that is the case, destructive resonance phenomena are likely to happen.

It has hardly been appreciated that, of the higher harmonics, the third cannot exist in a three-phase line, although it is the most prominent in the generator. (Unless the YY connection of transformers is used, which is not good engineering. But even in that case the triple harmonic appears only in the potential against ground, never in the voltage between the lines.) We need, therefore, consider the fifth harmonic more particularly;

so for instance, in a line 150 miles long, the frequency of the fifth harmonic is obviously five times that of the fundamental. Consequently, in a 60-cycle circuit we have 300 cycles, which is very closely the same as the natural period of the line. 60 cycles would therefore not be feasible unless the line were artificially loaded.

It is perhaps opportune to give an average value of inductance and capacity in high-potential lines. By assuming the inductance as 1.75 millihenrys per mile of wire, and a capacity of 0.0165 mf. per mile of wire, an error of more than 15% can not well be made, when referring to transmissions of from 30,000 to 100,000 volts and conductors from 0.25 in. to 1 in. in diameter. Since, furthermore, in these high-potential lines it is always necessary to have at least two lines in parallel, it is well to bear in mind that in doing so the ohmic drop is the same, whereas the inductive drop is one half and the charging current is twice as large as with one line. The reactance corresponding to certain inductance is expressed by the following formula:

$$\text{The reactance } x = \frac{2\,\pi\,n\,L}{10^3}$$

The charging current I_0 is expressed by the following formula:

$$I_0 = \frac{2\,\pi\,nC\,E}{10^6}$$

where n is the frequency, L is the inductance in millihenrys, C is the capacity in microfarads, and E is the voltage to neutral.

If L and C correspond to one mile of wire, x and I_0 obviously also refer to the same.

It is interesting to note in connection with this, that, since the voltage to the neutral in a single-phase system is one-half and in a three-phase system = 0.58 of the line voltage, the charging current per wire for a given line voltage is 16% greater in a three-phase system than in a single-phase system.

With the help of these constants, we can now readily calculate some of the abnormal phenomena.

1. ABNORMAL VOLTAGE AND CURRENT IN OPENING OR CLOSING A CIRCUIT

To determine this it is necessary to calculate the stored energy. The energy in joules (watt-seconds stored electromagnetically) is $0.5\,L\,I^2$. The energy in joules stored electrostatically is $0.5\,C\,E^2$. Where L and C are given in henrys and farads.

Therefore, if the line is disconnected at the moment the current has a given value I, energy is stored which must be spent in some way. The only path for the current is formed by the line capacity, therefore the line becomes charged to a certain voltage depending upon its constant; next it discharges through the inductance of the line, so charges again, etc. A current oscillates in the system until the energy is dissipated by the resistance of the line. Therefore, with low resistance there will be many surges; with high resistance, few.

The two energy equations become:

$$0.5\,L\,I^2 = 0.5\,C\,E^2 \qquad \text{thus} \qquad E = I\sqrt{\frac{L}{C}}$$

or

$$I = E\sqrt{\frac{C}{L}}$$

Substituting the average values given above we get

$$E = 325\,I \qquad \text{and} \qquad I = \frac{E}{325}$$

We see from this that the electromotive force induced on opening a circuit is independent of the length of the line.

Opening a switch at full-load instantaneous value of current. In a 60,000 volt transmission of 20,000 kw. the rise will be 60,000 volts per phase; consequently, the total voltage will be almost trebled. Interrupting the charging current will, however, give a very low rise, since the current is so small that there is no difficulty to be anticipated by disconnecting such line.

But, in connecting the line the moment the electromotive force is maximum, *a very considerable instantaneous current will flow*, namely, $\frac{E}{325}$. Consequently, with a voltage between the lines of 60,000, when the voltage per phase is 34,700, the current would be about 100 amperes; whereas the charging current is probably about 10 amperes.

It is also evident from this that we must use such circuit-interrupting devices as open when the current is small, preferably zero. From a great number of oscillograms we have found that our oil-switches break at zero value of current, and we find that no rise in voltage will occur when they are used. Indeed, from some oscillograms that have been made in which the circuit has been opened by air-switches, it would seem as if, when the line voltage is sufficiently high, the arc will keep on until the current value is decreased to such a small amount that, at the time of break, there is no serious rise in voltage. A gust of wind might, however, cause the circuit to be broken when the current is large, when, of course, a rise would take place.

It is also interesting to note that, since the rise in voltage is independent of the line voltage, we are likely to have relatively worse stresses with low-voltage systems; although, to be sure, if the voltage is sufficiently low, the likelihood of the current being interrupted at any point but the zero point is slight. These phenomena of large currents and high voltages in a line apply to grounded as well as non-grounded systems.

2. ABNORMAL CURRENTS AND VOLTAGE STRESSES IN CONNECTING A TRANSFORMER TO A SYSTEM

Outside of the ordinary stresses between adjacent turns, and winding against ground, there is a very high potential stress between the first few turns of the primary winding when the transformer is connected to a live line. The very first instant that connection is made, one part of the winding is raised to line potential, whereas the rest of the winding is still at ground potential. Consequently, the full voltage exists between the first turns. It is therefore necessary to insulate the first few turns extremely well as compared with the succeeding turns.

It is also evident that when being thrown on the line the transformer may sometimes take a much *larger current than the normal exciting current.* If the transformer when last used was disconnected from the circuit when the flux was at its maximum value, the density will decrease after a short time to about 70% of the maximum value, as can be seen by studying the hysteresis loop. If now the transformer is connected to the circuit at such a point of the potential wave as requires increasing flux, the magnetizing current must be very large, since the iron is already at 70% of the saturation point. At the next instant, however, the magnetic condition will adjust itself, so that the current is normal. The first large current is, of course, of very short duration, but might well be twenty times the exciting current or two or three times full load.

3. Abnormal Voltage in a Non-Grounded System

There has been a great deal of discussion about grounding or not grounding the neutral of transmission lines. For the very high voltages considered at present, I doubt very much if anything but a grounded system can be considered. When operating at such very high voltages, the difficulties of protecting a transmission, and indeed of building and installing the apparatus, increases materially. In the wiring and line itself, a minimum size of conductor, which already is quite large, is necessary in order to prevent corona effects. This corona involves loss in power and is a likely producer of nitric acid, which is detrimental to adjacent insulation.

Investigation of corona effects in parallel conductors—

Let I = current flowing in conductor.

Magnetomotive force per unit length in zone $= \frac{I}{2\pi x}$

field intensity $= 4\pi \times \text{m.m.f.} = \frac{4\pi I}{2\pi x} = \frac{2I}{x}$

and magnetic flux in the zone $= \frac{2I}{x} \times l \times dx$

thus total magnetic flux between wire and zone

$$= \int_r^R 2 I l \frac{dx}{x} = 2 I l \, {}^n lg \frac{R}{r}$$

neglecting flux inside of wire;

thus $L = \frac{\text{flux}}{I} = \frac{2l}{10^9} \, {}^n lg \frac{R}{r}$ henrys.

Therefore we can write the electromotive force corresponding to this flux $E = k \, {}^n lg \frac{R}{r}$

The flux between x and R is

$$L_x = 2 l \, {}^n lg \frac{R}{x}$$

and corresponding electromotive force

$$E_x = k\,{}^{n}lg\,\frac{R}{x}$$

therefore,

$$\frac{E_x}{E} = \frac{{}^{n}lg\,\frac{R}{x}}{{}^{n}lg\,\frac{R}{r}}$$

The potential gradient is

$$\frac{d\,Ex}{d\,x} = \frac{1}{x}\,\frac{E}{{}^{n}lg\,\frac{R}{r}}$$

Therefore the potential gradient at the surface of the conductor is $S = \dfrac{E}{r\,{}^{n}lg\,\frac{R}{r}}$ and at the inside of the outside sphere representing ground potential:

$$S_1 = \frac{E}{R\,{}^{n}lg\,\frac{R}{r}}$$

The stress is therefore as much greater at the conductor than at the shell as R is larger than r.

Obviously, when applying this to parallel conductors, we should use as R one-half the distance between conductors, and as E the voltage to neutral.

From a number of experiments, it looks as if the maximum stress that can be permitted in air is 100,000 volts per inch. Thus $S = 100{,}000$. Based upon this value we obtain the following voltages of corona:

	No. 10 B&S	No. 4 B&S	No. 000 B&S		
	$r=0.05$ in.	$r=0.10$ in.	$r=0.20$ in.	$r=0.5$ in.	$r=1$ in.
R	E	E	E	E	E
5 in.......	23000	39000	64000	115000	161000
10 in.......	26500	46000	78000	150000	230000
20 in.......	30000	53000	92000	184000	300000
50 in.......	34500	62000	110000	230000	390000
100 in.......	39000	69000	124000	264000	460000
500 in.......	46000	85000	156000	345000	620000

We see, for instance, that in a 60,000-volt ungrounded system, where the potential to ground can readily be 64,000 volts, the smallest wire that could be used in carrying the line through a wall having a hole 10 in. diameter is No. 000 B. & S. Any smaller wire would give corona affects. No. 4 B. & S. would, at the same voltage, require a hole of about 100 in. diameter.

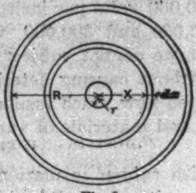

Fig. 1

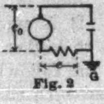

Fig. 2

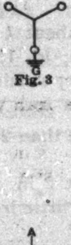

Fig. 3

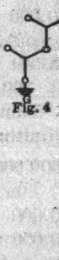

Fig. 4

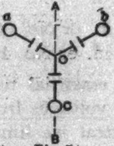

Fig. 5

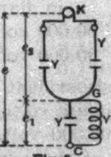

Fig. 6

It is also evident that if, as often is the case, the high-potential bus-bars are carried in compartments within but a few inches of ground, we must expect corona effects, especially where there is a sharp bend in the wires, whenever for some reason the voltage is increased above normal. Incidentally, we see the desirability of using large round bus-bars instead of small rectangular bars.

The dielectric strength of insulating materials is greater than that of air, so for instance, from a number of experiments, it seems that insulation of strips of rubber has a strength of about 350,000 volts per inch; oil of about 200,000 volts per inch; and varnished linen or paper between 250,000 and 300,000 volts per inch. It is evident from this that we cannot subject this insulation to higher stress than this without causing deterioration. In the following table is calculated how much insulation is necessary with various sizes of wires and materials of various dielectric strengths.

It is interesting to see that even with rubber insulation we should insulate a wire of 1 in. diameter with about 8 in. of insulation if subjected to 500,000 volts potential to ground. At 300,000 volts we should need 2.27 in. of insulation.

At 150,000 volts we should need 0.68 in. of insulation.

At 60,000 volts we should need 0.20 in. of insulation.

This would give no safety factor whatever. At 500,000 volts the smallest wire that can be insulated is about 1 in. in diameter; at 300,000 volts, 0.5 in. in diameter; at 150,000 volts, 0.20 in. diameter; and at 60,000 volts, a very small wire.

But limiting the stress to 140,000 volts per inch we find that:

For 500,000 volts the wire should be more than 2 in. in diameter.
300,000 volts the wire should be about 2 in. in diameter.
150,000 volts the wire should be just a little less than 1 in. in diameter.
60,000 volts the wire should be 0.20 in. or No. 000 B. & S.
30,000 volts the wire should be 0.10 in. or No. 10 B. & S.

It is evident from this that it is very essential to keep the maximum voltage down when considering voltages from 60,000 to 100,000 volts. By grounding the neutral we limit this to 58% of the voltage between lines.

Apparent erratic voltage between terminal and ground. When measuring the voltage between any of the terminals and ground, it is observed that it is not definite but depends, essentially, upon the resistance in the circuit. This, however, is natural, as can be seen from the following reasoning:

Let e be the voltage from terminal to ground; that is, the voltage across the resistance.

THICKNESS OF INSULATION IN INCHES WITH VARIOUS STRESSES AT SURFACE OF CONDUCTOR

	500,000 VOLTS TO GROUND			
r	$S=70,000$	$S=140,000$	$S=200,000$	$S=350,000$
0.05	5×10^{59}	5×10^{28}	2506×10^{16}	1256×10^{6}
0.10	1×10^{29}	3163×10^{10}	708×10^{6}	158500
0.20	6325×10^{10}	1125×10^{3}	53220	251.6
0.50	792400	628.9	73.46	8.189
1.00	1258	34.49	11.16	3.169
	300,000 VOLTS TO GROUND			
0.05	7925×10^{31}	1991×10^{13}	5236×10^{7}	1377000
0.10	3981×10^{12}	1995×10^{4}	322500	324.8
0.20	3991×10^{4}	8934	3598	14.29
0.50	2623.5	35.72	9.7	2.273
1.00	71.45	7.512	3.478	1.355
	150,000 VOLTS TO GROUND			
0.05	1991×10^{13}	99760000	161800	262.4
0.10	1995×10^{4}	4666	179.8	7.1444
0.20	8934	42.07	8.283	1.502
0.50	35.72	3.755	1.739	0.677
1.00	7.512	1.918	1.112	0.535
	60,000 VOLTS TO GROUND			
0.05	1380000	263	20.04	1.488
0.10	325	7.15	1.904	0.4546
0.20	14.3	1.5	0.6954	0.271
0.50	2.28	0.68	0.4108	0.2043
1.00	1.35	0.54	0.35	0.187
	30,000 VOLTS TO GROUND			
0.05	263	3.6	0.9525	0.2273
0.10	7.15	0.752	0.34477	0.1355
0.20	1.5	0.384	0.2232	0.1041
0.50	0.68	0.27	0.1748	0.0934
1.00	0.54	0.24	0.162	0.09
	15,000 VOLTS TO GROUND			
0.05	3.6	0.37		
0.10	0.752	0.192		
0.20	0.384	0.14		
0.50	0.27	0.12		
1.00	0.24	0.11		

e_0 be the generator voltage per phase,
x = capacity reactance of the system,
r = the resistance between the capacity and the terminal.

We have then:

$$\text{current flowing} = \frac{e_0}{r + j\,x}$$

and voltage across the resistance:

$$e = \frac{e_0\,r}{r - j\,x} = \frac{e_0\,r}{\sqrt{r^2 + x^2}}$$

With a generator disconnected from any line, the charging current against ground is, of course, very slight, so that x is very large. Therefore, for moderate values of r, compared with the values of x, we see that changing the resistance does not materially change the denominator, but the voltage e is proportional to the resistance, thus there is a constant-current effect. The more resistance is put in circuit the higher is the voltage. With infinite resistance the voltage is

$$\frac{e_0}{\sqrt{3}} = 0.58\,e_0$$

Effect of slight leaks in switches, etc. Assume next that the terminal of one phase through a slight leak is connected to ground, the voltage between the other phases and ground will then be almost doubled, being $e\sqrt{3}$

If there are two sets of generators running independently, and there is a slight leak from one terminal of one to that of the other, and also a slight leak to ground, there will be at times 3.5 times as great potential to ground as when the neutral is grounded. This condition might well occur when synchronizing machines or transformers. In circuits of moderate voltage, these voltages might not cause undue stresses, but with a normal voltage of 100,000 it is quite different.

But grounding a terminal does not always give the same results. A positive "good" ground does not cause the "statics" of an arcing ground. The reason is as follows: no matter how or where the circuit is made, as long as there is an arc there is a circuit. Usually this contains resistance, reactance, and capacity.

With a positive ground, the frequency impressed is that of the generator, and it would be but a chance if the values of capacity and reactance should be such as to cause more than slight resonance. With an arcing ground, on the contrary, the circuit is disconnected, and can, and will, oscillate at its own frequency, which is such as to give resonance, which means such as to give the maximum voltage and current.

To be sure, if, as in our lightning-arrester, the oscillations are damped out by a judicious use of resistance, no dangerous voltages occur, but, with accidental slight leaks or grounds, it is quite different. The voltages from ground might then be almost anything. Some protection is, of course, to limit the rise by grounded neutral.

In an ungrounded system, grave danger exists under almost all conditions of disturbed service. For instance, a lightning stroke disables some apparatus so that inductance is introduced in the accidental ground. Before the accident we had a perfectly balanced system, where the neutral, or ground potential, is symmetrical in reference to the line conductors, and governed entirely by the ground capacities represented in Fig. 5 as three condensers. If now one line is grounded by an impedance, the neutral will be displaced along line AB.

For convenience in demonstrating, we can change the diagram to a single-phase system, making due allowance, however, in the final conclusions—we will reconstruct the system to another shown in Fig. 6.

Let Y represent the admittance of each condenser and Y_1 the admittance of the impedance connected to ground, which is electrostatically the same as connecting impedance between the line and the point of neutral potential.

We have then the joint admittance between C and $G = Y + Y_1$, therefore the joint impedance $= \frac{1}{Y + Y_1}$. The joint admittance between G and K is $2\,Y$, therefore the corresponding impedance is $\frac{1\,Y}{2}$. The total impedance is therefore:

$$\frac{1}{Y+Y_1} + \frac{1}{2\,Y} = \frac{3\,Y+Y_1}{2\,Y\,(Y+Y_1)}$$

The current is therefore, $\frac{2\,e\,Y\,(Y+Y_1)}{3\,Y+Y}$

$$E_1 = \frac{2 E Y (Y + Y_1)}{3 Y + Y_1} \frac{1}{Y + Y_1} = \frac{3 Y + Y}{2 e Y}$$

$$E_2 = \frac{2 e Y (Y + Y_1)}{3 Y + Y_1} \frac{1}{2 Y} = \frac{e (Y + Y_1)}{3 Y + Y_1}$$

$Y = g - j b$, where g is energy component of current; b is wattless component of the current in the condenser.

$$Y_1 = \frac{r}{Z^2} + \frac{j x}{Z^2}$$

where r is energy component of electromotive force and x is wattless component of electromotive force.

We will assume that there is no leakage in the line, therefore $g = 0$ and $Y = -j b$.

We will also assume that there is no resistance, but only reactance in the accidental ground of the line.

Thus $r = 0$ and $Y_1 = j \frac{1}{x}$

We get then $e_1 = \dfrac{2be}{3 b - \frac{1}{x}}$ and $e_2 = \dfrac{\frac{1}{x} - be}{\frac{1}{x} - 3 b}$

If x_1 = condenser reactance, then

$$e_1 = \frac{2 e x}{3 x - x_1} \quad \text{and} \quad e_2 = \frac{x_1 - x}{x_1 - 3x} e$$

1. Ground made by infinite reactance. (No ground.)

We have then $x = \infty$, $e_1 = \frac{2e}{3}$ and $e_2 = \frac{e}{3}$

Therefore in our diagram, the neutral lies at O, and the ground is symmetrical in reference to the three lines.

2. $\frac{1}{x} = b$, thus $e_2 = 0$, and $e_1 = e$

In this case the neutral lies midways between the two other conductors, and 0.870 from the grounded line.

3. For $\frac{1}{x} = 3\,b$ e_1 and e_2 both become infinite showing that, under such condition, the system would be subjected to infinite potential.

b is the susceptance of the condenser, therefore $\frac{1}{b}$ is the condensance or capacity reactance. We see, therefore, if one line is grounded by a reactance of one-third the condenser reactance, the system is subjected to infinite stresses, even at normal frequency. Energy losses, however, limit the value considerably.

We might, for instance, in such accident have the line conductors 3 ft. apart and separated by 6 ft. from any wall, and yet upon inspection find that each line was connected through flames to the wall, but that there was no flame between the conductors.

Obviously, if the impedance had been grounded through an arc, high voltages would have resulted, almost independent of the relation between capacity and inductance. The remedy, in that case, would have been a grounded neutral.

Static stresses of generator and transformer windings introduced by accidental ground. A ground might well cause serious breakdowns by the static effect only. Consider, for simplicity's sake, a single-phase system, consisting of a generator, a transformer, and a line.

There is, of course, a certain capacity between primary and secondary of the transformer winding. There is also a certain capacity between the generator winding and the frame, which is the ground.

With the two lines symmetrical and well insulated, there is a balanced capacity against ground, thus the high-potential coils of the transformer are at ground potential; consequently, the low-potential coils and the armature windings are also at ground potential. If now one line becomes grounded, the potential of the coil against the ground is obviously one-half of the line voltage. Consequently, the low potential winding acting as the other plate of the condenser, is also charged to a certain potential, the magnitude of which depends upon the relative capacity of the generator winding to ground and the capacity between the transformer windings. If they are the same, then one-half of the line voltage is divided equally between the primary and secondary of the transformer and the generator winding to ground. If the capacity between transformer coils is twice that of the generator winding against ground, then the generator winding will be subjected to $\frac{2}{3}$ times $\frac{1}{2}$, or $\frac{1}{3}$ of the line potential.

We can readily see from this, when a ground occurs, how the generator might possibly break down, and how in such cases it is important to get at all facts. The remedy is a system with grounded neutral.

How to ground the neutral. Must we ground the neutral perfectly, or can we use resistance or reactance? Without going further into the question, it is evident from the preceding instance that a reactance in the ground connection is not advisable; there are, indeed, several good reasons, but resistance needs some further discussion.

In moderate voltage systems, say up to 15,000 or 30,000 volts, perhaps even higher, resistance is feasible, since under normal operation the stresses are those of a grounded system. When, however, one line is grounded and the current is limited by this resistance, its function as a neutral ceases, and, as far as voltage stresses are concerned, the system might as well not be grounded. It saves, however, a shutdown and permits the systems being rearranged without interruption of service. For transmissions of very high voltage I believe, however, that a good solid ground is best; since any considerable rise might strain the insulation above its safe limit.

Discussion on "Line Constants and Abnormal Voltages and Currents in High-Potential Transmissions".

Frank G. Baum (by letter): The writer gave approximate rules for determining the rise in voltage, due to interrupting a given current, at a meeting of the Pacific Coast Transmission Association in 1902 and before the Electrical Congress at St. Louis in 1904. The rule given was

$$E = 200\,I$$

where I is the actual value of the current in amperes at the time of interruption. This does not exactly agree with the rule given by Mr. Berg. The important fact shown is that the higher the voltage the smaller the excessive strains due to switching, etc. The approximate rule will undoubtedly explain many things happening on lower voltage systems that are charged to lightning, etc.

Surges or resonance occur in any transmission system independently of how the transformers are connected. The statement that certain transformer connections eliminate resonance should be qualified, as it is liable to be wrongly interpreted.

NOTES ON HYDROELECTRIC PLANT ORGANIZATION AND OPERATION

BY FARLEY OSGOOD*

In order to discuss the several branches of hydroelectric plant organization in logical sequence, it seems desirable to divide the subject into two general headings: physical and personal. The general heading physical organization may be more closely followed under the subdivisions: hydraulic, power station, and line.

HYDRAULIC DEPARTMENT

The first matter to consider on the hydraulic end of a system is the amount of water available for power. If the source of power is of such magnitude that only a portion of the available water is needed to fulfil the requirements of a proposed development, the study will be along different lines from a development which is to take the entire discharge of a river or reservoir system. Unfortunately for those interested in water-power possibilities, there are not many sources of supply which will satisfy the demands by the use of but a portion of the water obtainable. As the greater percentage of power developments require the use of the entire source of water supply, this paper will deal with such types of installation.

The department of Geological Survey of the United States government has accumulated a vast amount of data regarding stream-discharges, drainage-areas, etc., throughout the whole country, and there are few powers under consideration which are not at least partly covered by information easily obtainable and of great benefit to the investigating engineer. With government records in hand, a careful study of the surrounding country, of a possible site, should enable the investigator to determine the limitations of development. The inclination is to become over enthusiastic concerning a power study, which naturally leads to disastrous results, as it means, if followed too far, that an installation will be recommended greater than can be used to its full benefit continuously.

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*The writer desires to express his thanks to Mr. Frederick Miles for assistance in obtaining details of operation.

In this age of rapid development and performing of great engineering feats, we sometimes, perhaps too often, lack inclination to listen to our elders when they discourse on the happenings of their boyhood days; but when making a study of a water-power development it is good policy to make friends with the oldest inhabitant and his contemporaries, to draw them into tales of the terrible floods, awful ice jams, and droughts; for history repeats itself, we are told, and any recurrence of such happenings as may be related by our old friends of the region might blast forever the reputation of the power investigator, if proper provisions are not made to contend with these difficulties. The minimum and maximum discharge must be determined, and then the intermediate periods worked out to show the number of months in which the average or mean discharge is available for practical purposes. This is best shown by the plotting of curves based on calculations giving daily discharges; and the study should cover a period of as many years as can be covered by accurate information. The maximum discharge can seldom, if ever, be fully utilized; the minimum discharge must be guarded against; and the conservative mean discharge will be used as a basis for determining the canal section, sizes of water wheels, etc.—all, of course, to be considered together with the amount of fall obtainable.

Having decided that a water power will warrant development, the next step is to study the most advantageous location of the plant. There must be a dam; that is, when the entire supply is to be utilized, and the dam must be so placed and constructed that it can never be carried away by floods, ice jams, or other abnormal conditions. Generally speaking, dams of to-day are built of concrete, many solid, some rock-filled, and several hollow; in the latter type the concrete being merely a shell, as it were, reinforced with steel. The ideal dam location will have ledge for a base, and ledge to which to tie each end of the dam, but as this is by no means always possible, false floorings, deep-front cut-off walls, long wing-walls at the ends of the dam, and many other special features have to be resorted to for the sake of security.

If a sufficient fall is obtainable at the chosen dam-site the development will be a simple one, so simple perhaps that a portion of the dam may be used as one wall of the power station, thus enabling the engineer to make the least expensive design of a complete hydraulic plant. Usually a canal is necessary in order to get the full benefit of all possible head. This canal may be an open one, or a wooden or metal tube. When practicable, the open canal is the least expensive. Many developments necessitate a tube, especially in cases where the storage-pond is at the top of a mountain and the power station at its base. Wooden tubes reinforced with metal hoops are common throughout the Northwest, but eastern practice seems to favor the metal tube. If an open canal is decided upon, it is desirable to have a waste-gate arrangement ahead of the intake or controlling gates of the canal proper. This is especially true when the spillway of the dam is a short one, as sudden rises of a pond may be difficult to control; but if the location of the dam is such that the natural discharge-area of the pond or river can be considerably increased, the provision for wasting water ahead of the controlling gates is not really essential. If the development is to include waste-gates, a metal gate is preferable to a wooden one on account of its strength and greater ease of operation. A stop-log arrangement at the mouth of the canal cut will make it possible to dry the canal section ahead of the canal controlling gates, thus making it possible to make repairs to all the gates in the headworks. If waste-gates are used, it is a good plan to have one of them open from the top down, thus taking off surface debris, while the other gates should open from the canal bottom up, thus ensuring the ability to dry the head works section when necessary.

If the canal is a long one, and especially if it is so situated as to become the drain of a hilly surrounding country, it is well to provide spillways along the canal, the top elevation of which should be lower than the elevation determined for the berm of the canal bank. Care must be taken properly to protect the canal bank at these spillway points, as any lack of control of this waste water might destroy the canal wall. At the lower or power-house end of the canal a forebay or small reservoir development is a good feature in order to steady the water at the entrance of the penstock or flume to which the water wheels are directly connected. If the canal is a long one and of such small cross-sectional area as to necessitate any appreciable velocity of the water, a forebay is practically indispensable, else sudden increases of load on the station will cause great discomfort owing to the inability to feed the water wheels fast enough. It is well, too, to provide the forebay with an ample spillway, as a final safeguard in times of flood occasioned by either natural or accidental causes. All the spillways along the canal and at the forebay should contain waste-gates in order to make it possible to drain the canal quickly in case of accident to any part of it. If a portion of the canal wall goes out, or even starts to fail, many thousand dollars may be saved by being able quickly to relieve the injured part of the water pressure against it. In a tubular canal care must be taken to provide secure anchorages at proper intervals, as there will be a constant tendency of the flume to slide downhill, although, of course, the weight of the water carried by the flume will greatly increase its frictional grip on the surface upon which it rests.

In either an open or closed canal development, trash-racks are necessary to keep floating substance out of the wheels. Trash-racks are usually made of metal slats, or metal bars, arranged in sections, and preferably designed in vertical sections as well. A rack-section should not exceed four feet in width; two feet is better. The rack-hoisting machinery should be housed, and the front of the building can be carried out over the racks with the front wall built down to form a curtain wall in the water ahead of the racks. This curtain wall acts both as a boom and as a means of sealing the building. It is best to heat the rack building during the ice season, as it will help to keep the racks free of ice, to say nothing of the comfort to the man in charge.

If the racks are built in vertical sections, properly pinned together, a rack can be easily removed by one man with the aid of a small differential chain-hoist which should be part of the rack-house equipment and designed to run on an elevated track placed so that the hoist may be brought directly over each rack-section. The vertical rack-section allows sufficiently light sections to be comfortably handled when out of position, thus greatly facilitating cleaning and repairing.

If the power station is not to be directly connected to the forebay, a penstock or flume will be necessary. This penstock must be protected against water-hammer occasioned by the sudden release of, or wide swings in, the load on the station, which would, by means of the water-wheel governors, shut off the passage of water through the wheels, thus leaving no outlet for the water at the lower end of the penstock. It can easily be seen that should this condition arise in a penstock of any material length without relief devices, it would not be unreasonable to expect the penstock to burst. This would bring about a calamity for which few engineers would care to be held responsible.

This water-hammer, or hydraulic ram effect, is overcome in two ways; first, by the use of a relief-valve near or at the lower end of the penstock, this valve to be set to operate at a pressure slightly higher than the normal operating pressure on the penstock; secondly, by the continuation of the penstock at its lower end to a perpendicular height equal to the elevation of the water-level in the forebay—the continued section usually to be of a somewhat smaller area than the main penstock. The latter, or standpipe method, is, of course, only practicable when the discharge from the top can be properly cared for outside the power station. Where the development necessitates the terminating of the penstock in or under the station, the relief valve is used with its proper discharge tube into the tailrace.

To guard against the rather unusual occurrence of having the penstock in danger of collapsing due to the water being suddenly taken from it, it is desirable to place one or more vent-pipes at the upper end of the penstock. The vent should be large enough to perform its duty when called upon, a fact not always appreciated by the designing engineer. The vent-pipe should be encased and kept from freezing. If a stand-pipe is part of the outfit, it should be encased and kept from freezing, and the surface-water at its top should receive sufficient heat to keep it open. The heating of the stand-pipe may be easily accomplished by either steam or electricity; it is best handled by having it included in whatever system is used to heat the power station.

It would at first seem proper to include the water-wheels in these notes on the hydraulic department, but as the wheels really form part of the power station equipment, and are usually wholly or partly within the walls of the building, they will be considered under that classification.

POWER-STATION DEPARTMENT

As soon as the power station comes into consideration, it is necessary to go to the other end of the line and study the field of work to be fed by the station, as surely the nature of the load must determine the characteristics of the generating units. If the power development is to be one of any great magnitude, it will usually be designed to do general work including street and commercial lighting, electric railway service, and the factory power business—thus carrying a direct load, as well as a synchronous and inductive load.

Without question the current will be alternating. General practice favors three-phase current. As street lighting is apt to be a feature, the generating will be at a high number of cycles; 40 at least, and usually 60. Railway men prefer 25 cycles, of course, but that part of the load can be made a sub-station study. As these notes bear directly on the power and transmission end of the business, and as the time is limited, we will not consider the secondary end in this paper. After the character of the load is known, and assuming that three-phase, 60-cycle alternating current is to be furnished, the next step is to determine the transmission voltage.

The principal factor in determining the transmission voltage is the length of the proposed line. If the field of work is near at hand a low voltage maybe desirable, even as low as 10,000 volts, or in special cases 6600 volts. Under such conditions step-up transformers are unnecessary, for a machine voltage up to 11,000 volts is entirely within the limits of good practice. If, however, many miles of line are required, the transmission voltage should not be lower than 24,000 or preferably 33,000. Perhaps 50,000 or 60,000 volts would be better to meet all the conditions. As 33,000 volts is a very common transmission voltage, we will continue under the assumption that these notes bear on plants of that or a higher voltage, thus bringing in the necessity of step-up transformers.

Having learned the character of the load and determined the transmission voltage, it is now necessary to return to the water-wheels to find out what speed may be obtained from them. This, of course, will be determined by the amount of available head, and that factor will in turn determine the voltage of the generator units. As a rule, it is not advisable to have the generator voltage above 2300 volts, unless the generators are to have a very large kilowatt capacity, say over 2000 kw. The water-wheel and the generator must be considered together, for an arbitrary specification feature of one might well be beyond the mechanical or electrical possibility of the other. When generator requirements and water-wheel limits cannot be brought into a reasonably close relationship, then gears and belts have to be resorted to, and that is not desirable. Direct-connected work is the best, but an engineer should not ruin his station by impractical arrangements just to obtain direct-connected prime movers.

The available head is the first point of interest to the wheel designers, and secondly the flow of the stream. In low heads, and therefore moderate pressures, the wheels are sometimes placed in chambers in the forebay or headrace, the shaft running through the station wall, the generator being direct connected to it. When possible, this makes a very good arrangement, but provision should be made to shut the water out of these wheel-chambers, and also to drain these chambers in order to get at the wheels for inspection and repairs. As this arrangement of wheels will start with the opening of the turbine-bucket gates and draught-tube, it does away with the necessity of hydraulic-valve-operated gates, or in fact all other gates, which is greatly in its favor. In a fairly high-head development a penstock is required and the wheel-chamber scheme is impracticable.

In high-head work the wheels are usually inside the power station building and are encased in a large metal chamber used as a water-jacket. This arrangement will require some sort of a gate within the station, and it will be best to have the gates hydraulically operated, but care must be taken to have the operating device large enough to do its work unhesitatingly. It is well to have a second gate outside of the building in order to keep water out of the wheel-cases when the interior gate needs repairing.

A by-pass around the gate is essential in this type of wheel, in order to fill the water-jacket of the wheel before attempting to raise the interior gate, thus helping to equalize the pressure on each side of the gate, and greatly relieving the gate-raising equipment. This by-pass arrangement can be cast in the gate and controlled by a hand-operated valve. This scheme is preferable to a pipe and valve tapped into the intake pipe and wheel-case.

An electrically driven device can be used to operate these wheel-gates, the motor being driven by current from the exciters, thus putting the matter in the hands of the operator—a desirable thing in case of accident to a wheel requiring a quick shutdown. In very high head-work impulse wheels are used, the governors being used to deflect the stream from the nozzles rather than to open or close a gate equipment. There are many makes of good water-wheels in America, the choice is merely the decision as to the wheel best suited to the conditions at hand.

The water condition again becomes a factor when determining the capacity of the generator units, for it is desirable to have at least one unit which will be about equal to the minimum kilowatt output of the stream during periods of low water. It is advantageous to have all units of an equal capacity, but in low heads, with streams of great difference in minimum and average flow, this is often impossible. If all units are of equal capacity, it makes them interchangeable and thereby greatly reduces the stock of extra parts to be carried.

When, however, the average flow of a stream would warrant 2000-kw. units for general service conditions, but the minimum period would not develop over 500 kw., it is at once apparent that a 2000-kw. machine would give poor service during the low-stage period; for a machine works best when loaded, or nearly loaded, to its rated normal capacity. These points are to emphasize the fact that the hydraulic and electrical features must be considered together.

The most convenient arrangement of units is in a single row, and if possible on horizontal shafts with plenty of room between units for the water-wheel governors, and for the operators to pass comfortably between moving machines. Many a station is ruined by crowding the machines, and as water-driven stations are generally in rather isolated locations, the matter of land-cost is not an alarming factor, and, therefore, lack of room is inexcusable.

The exciting units should be of sufficient capacity to run the whole station with but one exciter. Motor-generator sets or electric-driven exciters are a good thing, as after the station is in operation the water-driven exciters can be shut down, thus saving water. There must be a water-driven exciter, or else the station cannot be started up. There should be two water-driven exciters, one reserved as a spare. It is possible to carry an exciter on the main shaft of the generator, usually on the outer end. In some cases each machine may carry its own exciter, one or two machines only may carry exciting units of sufficient capacity for the entire station. Belted exciters, from a pulley on a machine shaft, are sometimes used, but rarely in any but very small plants.

Individually driven exciters are without question the best type. An exciter driven by a larger unit necessitates the wasting of water. If for any reason the larger generator is unable to carry its portion of the load—and all machines require attention and repairs—the arrangement of each generator carrying its own exciter is a poor one, for if the water-wheel speed is affected, or the generator speed is momentarily changed by load fluctuations, then the exciter voltage follows the change. Frequently, then, the very opposite effect from the desired one is the result.

The location of the exciters is largely determined by the location of the operating switchboard, as the exciting machines should be in sight of the operator at the switchboard. The best location for the switchboard is on a gallery high enough from the floor to allow the operator to see all machines at once. The switchboard, if it does not extend the entire length of the gallery, should be in the centre; in such cases the water-driven exciters will be most easily observed if directly opposite the centre of the gallery, with the electric driven exciter, if one is used, on the gallery. If for any reason the switchboard must be on the floor, the exciters should be in sight from it; if the switchboard has to be at the end of the building, as is sometimes the case, have the exciters on the end instead of in the centre of the station.

Water-wheel governors give the best results when placed as near the wheels as possible; they should be electrically controlled from the switchboard, thus making it possible for the operator instantly to change the action of a governor. There are many types of governors, the foreign types being especially good for very large unit work, but there are American-made governors which are very efficient, giving entirely satisfactory results. American governors can be purchased for about half the cost of an equally good foreign make.

If the conditions will permit of a gallery, a very comfortable layout can be planned. The low-tension bus-bars are well out of the way, yet accessible, if placed overhead at the back of the gallery. If such an arrangement is chosen, it is a convenience to have each set of bus-bars at different heights from the floor, but not over one another. The low-tension bus-bars can also be well arranged if placed in hangers just under the floor of the gallery, although in this arrangement the switchboard wiring cannot be so well cared for, as proper bus-bar clearance must be provided.

Between the machines and the bus-bars there should be both knife-switches and oil-switches, the former to protect the latter, as sometimes an oil-switch fails to act properly. The oil-switches should be motor-driven, but the hand-operated oil-switches are cheaper and are safe for low-tension work.

All cables should be carried in ducts or troughs, and these conduits should be so arranged that they cannot retain water should any get into them accidentally. Where the cables are carried along walls, it is good practice to run them between cement panels, which oftentimes are enclosed except at the cable supporting points—where square holes are left—to enable the operator to inspect or change a support. The oil-switches are well located if placed under the gallery, though some operating engineers prefer them on the gallery directly underneath the low-tension bus-bars. Oil-switches are, of course, placed in individual chambers, often iron, and just as often brick or cement. It is not an unusual practice to close in the front of the chamber with a metal curtain, but by so doing the action of the switch is concealed. It is far better to have a thick-glass panel in the front of the switch-chamber, this glass to be set preferably in a metal frame. These frames can be built to contain a light of glass for each phase of the oil-switch, thus making it possible for the attendant to see the switch at all times, which is desirable both for mechanical and personal reasons.

A good position for the generator field-rheostats is on the gallery at the back, or immediately back of and above the switchboard. In any event, rheostats should not be placed under the gallery floor so that the heat from them will heat the floor of the gallery.

The switchboard is best located in the centre of the gallery and far enough back to enable the operator to pass in front of it without danger of his clothing coming in contact with any apparatus on the board, so he can safely turn his back on the switchboard when he is watching the action of the equipment on the floor of the station.

The voltage-regulators can be placed on a panel in the switchboard, preferably on or next to the exciter panels, or they can be hung on supports at the end of the switchboard.

The synchronizing device should be placed so as to be visible from the governor of every unit. In long stations two synchronizing indicators are desirable, being hung to swing at each upper corner of the switchboard.

Automatic line devices are essential, and excellent results are obtained by the three-phase bellows type time-limit overload relay, the same to close the circuit on the motor operating the line oil-switch, thus opening the line. The device itself can be placed on the back of the line panel of the switchboard, but the transformers for the relays should be placed immediately back of the low-tension side of the step-up transformers. This placing of these relay transformers is particularly desirable when there is more than one transmission line and the lines are operated in parallel.

If the relay transformers are not placed on the line side of the oil-switch, especially the paralleling-switch, there will be a flow of current through the paralleling-switch, which will at times make the relay fail, or at least so delay action that its service is too late, often causing uncomfortable results.

Many engineers prefer to have the high-tension chamber of a development in a separate building; this is not necessary, but the high-tension room should be entirely separated from the operating room by a heavy fire-proof wall, either brick or concrete. A suitable layout of the high-tension chamber of a power system is of great importance, the chief requisite being plenty of room. In three-phase systems, single-phase step-up transformers should be used, and the oil-filled water-cooled type is the best. The equipment connected to the high-tension end of the system and to the transmission lines receives the greatest insulation strains, and an oil-filled water-cooled transformer has a much higher insulation breakdown point than an air-blast transformer.

If the transformers are subjected to abnormal pressures, as in the case of lightning storms, surges, etc., it is unusual to have more than one fail, as the very failure discharges the disturbing high pressure; therefore, if single-phase transformers are used, the station loses the capacity of but one-third of the bank, and if spares are not available, the remaining two transformers may be re-connected and put into service. If three-phase transformers are used, much inconvenience may result from a breakdown. Single-phase transformers are more costly than three phase, but the money is well spent.

The cables from the line oil-switches will terminate in some sort of a bus-bar arrangement, to which will be connected the low-tension leads of the step-up transformers. These bus-bars should not be supported on hangers fastened to the transformer cases, but should be placed on the wall back of the transformers or one on a separate bus-bar supporting frame.

The terminals of the transformer leads should be split or of some quickly detachable type, or else much time will be wasted in getting an injured transformer out of service and making the re-connection of the remaining two of the bank.

A hoisting crane is a dangerous thing in most high-tension rooms, and therefore it will be a convenience to have a flush-track under and in front of the transformers. The transformers can be jacked up on to a low truck which will run on the tracks, or each transformer may be equipped permanently with wheels to run on the track.

As the failure of a step-up transformer is really a serious matter, and as such an accident may occur at the time of a peak load, it is good insurance to carry an extra bank of transformers, the same to be ready for service and arranged to be cut in merely by the throwing of a set of switches. A single transformer as a spare is of course better than no spare at all, but the spare bank is the true solving of the problem.

Between the step-up transformers and the high-tension bus-bars come the multiple-switches, or the switches so connected as to make it possible to cut in any bank of transformers on any outgoing line. These switches are usually knife-switches, although in very large developments high-tension oil-switches are used. For most purposes the knife-switches are sufficient, as the transformer bank is killed by the oil-switch on the low-tension side. If many banks of transformers are used, or if there are several outgoing lines, the connections between the multiple switches and the high-tension bus-bars may be much simplified by the use of sectionalized bus-bars. To the high-tension bus-bars are connected the transmission line, and these connections should be made through switches; knife-switches are sufficient. At first this may not seem necessary, but the induction effects from parallel transmission lines usually make these switches the best friends of the operators.

Just before the lines leave the high-tension room are the taps to the lightning-arresters. Some engineers prefer to have the protective devices in a separate building, but if the high-tension chamber is well arranged it is perfectly safe to install the arresters in it, and it is a good thing to have the action of the arresters observed by the operator. As the lightning-arrester problem is a study in itself, and as the writer is preparing some detailed information to be used at a future meeting, supplementing the paper given by him at the 1906 annual convention, it hardly seems wise at this time to get too deeply into this very fascinating subject. The arresters should be given plenty of room and should be installed so as to be quickly and easily handled, preferably within reach from the floor. If two or more transmission lines are used, it is good practice to have two complete spare arrester equipments, no matter what type of arrester is used.

Reactance or choke-coils in the line between the arrester taps and the high-tension bus-bars have been proved to be of great benefit, many a bus-bar insulator and transformer lead having been saved by their use.

Beware of the use of slate as a material for the hoods through which the lines pass in leaving the building. Glass is the best material. Simply a hole in the wall is sufficient, but it is desirable to be protected from the cold air in winter and also from small birds, who seem to feel that the power station is built for their special convenience.

Space, plenty of it, is the secret of good high-tension chamber design. If any crowding has to be done, let it be anywhere but in the high-tension room, or else forever keep away from the man who runs the station.

LINE DEPARTMENT

A few years ago the question of material for a pole line was scarcely given a thought, as wooden pole construction was a universal practice. Experience brought out the fact that the poles which lasted the longest were of wood indigenous to the locality in which they were used. Wooden pole lines through the south were subject to attacks from insects of various kinds, and the high voltages coming into favor set the wooden poles on fire when an insulator failed, and so metal poles became desirable and in many cases a necessity. Generally speaking, it is economical to-day to construct a metal pole line, and it is more satisfactory from an operating standpoint.

Metal towers vary greatly in price, as a simple tower consisting of a large iron or steel pipe guyed four ways will not cost over $70 placed, while a heavy angle-iron tower, or iron-pipe tower, built up in triangular or quadrangular formation, may cost $175 to $250 placed. The lattice tower built with foot plates to bolt to a concrete base can be made very costly when finally placed. The maintenance and depreciation charges against metal towers are very much lower than against wooden poles. The towers being stronger and usually somewhat higher, the section-lengths may be increased, thus making it possible to have fewer towers than wooden poles. This is a saving; it decreases the number of insulators required, and thus decreases the number of possible points of breakdown. The towers are virtually indestructible, and the fact that they ground the system in times of trouble is not a great detriment but is often a real benefit.

The question of copper or aluminum conductors is still an open one, there being many points in favor of each. There is not a great saving in the use of aluminum, as the market price is governed by the market price of copper. The electrical properties of aluminum, as compared with copper, make it necessary to have nearly twice the sectional area in an aluminum conductor, so, all things considered, the net financial result is not so greatly in its favor as is generally supposed. Copper is more quickly obtained on orders, but aluminum is more quickly put in place, as it is so easily handled on account of its lightness. Practice indicates that a copper conductor will remain intact at the point of an arc for a longer time than will aluminum, and while this is a good feature on a wooden line—it may burn off the cross-arm, and thus clear the trouble—it is impossible on a complete metal line, as there is nothing to burn off and a sustained ground on the line may bring failure elsewhere in the system.

At first it would seem that a modification of a metal line is advisable, and therefore a metal tower carrying a wooden cross-arm would be good practice; for with such a combination the system is benefited by the better pole, while it still retains the benefit of the destructible arm. As a matter of fact, the percentage of disturbances which burn themselves clear without causing a shutdown to that particular circuit is very low, and the metal arm and pins seldom require renewal. Reinforced concrete poles, both round and square, are being tried, but at present there are no definite data concerning them.

Where duplicate and parallel lines are built, the poles or towers should be so placed that the phase wires nearest each other on the two lines should be at least 25 ft. apart, thus giving plenty of room for a phase wire to break and fall without whipping into the other line.

Porcelain insulators have proved to be the best type for high-tension work, on account of their superior mechanical strength and ability to withstand great temperature changes.

A telephone line on the same pole line as the transmission line is worth its cost as a trouble indicator, as the telephone instrument bell reveals the slightest ground on the system. Such a line is likely to be heavily charged from the transmission line, making it very uncomfortable for the patrolman if he is careless in making his tap to it with his patrolling set terminals. This induction effect is, of course, relieved by transposing the high-tension wires. The telephone wires should be transposed about every third section. Although such a telephone line will show a surprising voltage between one side and the ground, it will be perfectly quiet, giving excellent transmission service.

A telephone service between the power station and the sub-stations on a pole line other than the transmission line is practically a necessity, as during times of trouble on the transmission line the telephone line on that pole line is put out of commission or is at least unsafe, and it is during times of trouble that the telephone service is most wanted. Often it is possible to obtain a private service from the public telephone company which will be less expensive, all points considered, than the fixed charges on an isolated private telephone plant.

ORGANIZATION OF EMPLOYEES

The organization of the operating force in an hydroelectric power system is less complicated than in a steam system. Fewer attendents are needed at the power station, for nature not only provides the element of power, but by the simple law of gravity brings it to and takes it from the station.

On the hydraulic end should be a man thoroughly acquainted with the physical features of the property he controls, for there are generally points in any development which need watching, and all maintenance work should be carried on without shutting down the plant. The canal or tubular flume, if the latter type is adopted, needs constant inspection, for leaks must be anticipated if possible, and preventive work started. The open seasons bring leaves, timber, and other debris into the pond and canal; the frost season has its terrors, for the effects of the force of frost are incalculable; and the winter seasons, especially in the New England and northern sections of the country, bring anchor-ice, frazil-ice, and sometimes great masses of ice—all of which do their utmost to overcome the efforts for continuous service. The intake gates usually have to be attended to, to meet the varying load conditions of the day, and as most plants are quite away from points of population, a maintenance force of laborers and teams has to be maintained.

There are so many different conditions of development and location in such systems that it is impossible to recommend any exact form of organization, as really no two can be quite alike. The power-station superintendent must of course organize his force to meet the exigencies of the service, but it is seldom that he will require more than three men on a shift, and, unless the station is of enormous capacity, more than two men: an operator, and an assistant can handle it, but this of course depends on the layout of the station. These station men must be clever mechanics, as usually skilled help is not quickly obtainable, and as it requires so few men to handle a station the system can afford to have a high class of operating attendants.

If the system is not too large it is desirable to have the station superintendent in control of the hydraulic superintendent, thus ensuring harmony between the departments, which is of vital importance. If a development is of such magnitude as to require the entire time of a superintendent for each of the departments under consideration, it will probably warrant some sort of a position for a man to whom both superintendents will report, thus still bringing the responsibility for the operation of the two departments under one head. The line department should have at its head a superintendent capable of building, repairing, and operating the lines; for if continuous service is to be maintained the various branches of the work are inseparable from an executive standpoint.

The patrolmen, or line inspectors, will probably have time to make all ordinary repairs, and the number required is determined largely by the length of the line, but particularly by conditions of accessibility. The line superintendent would naturally report to the general operating head of the system.

Some Operating Experiences and Requirements

The first requisite in an operating force is a thorough knowledge, on the part of each member, of the detail of the work in hand. These operators should be placed so that they can work to the greatest advantage to themselves, and hence to the greatest benefit of the employer. The adage, "You cannot fit a round peg into a square hole" is one which applies directly to an operating organization, for many a force of good and able individuals is ineffective simply on account of improper arrangement.

The second matter of importance, which is almost as essential as the first, is a spirit of good fellowship between all employees. This spirit is brought about chiefly by the feeling of individual responsibility and loyalty to the company or employer. The development of this spirit is in the hands of the chief of the operating department. If this feeling of individuality is properly developed, so that each member, no matter how low his position, feels that he is a spoke in the wheel of the necessary organization, wholesome rivalry and interest will be the result, the effect of which will be so great that the operating chief can accomplish many things in the line of good service, clear records, beneficial recommendations, etc., which without this feeling of coöperation would be almost impossible. The employee feels, and the employer should know, that this or that person is not obliged to work for that particular concern; but the employee should feel, and be made to understand, that so long as he does work for the concern, he does so with a smile.

The personal equation of an operating system is one to be solved before the final approval of the designs; by this is meant how much responsibility is to be placed on automatic operating devices. It is possible to work out a system so complete in its complication that one or two operators may control every detail of a plant. Such a scheme might be very advantageous when every part of the plant is running smoothly, and acting in an entirely normal manner, but unfortunately hydroelectric systems, like human systems, do not always run along without difficulties. In the good old days there were no automatic devices, and men took chances in operating plants that would be considered to-day as quite beyond the limits of good practice.

It is a safe plan to have a plant so arranged and equipped that in times of trouble the master mind may be relieved to the extent of having an assistant locate and cut out the disturbing element.

Some of the following actual operating experiences of the last few seasons, which occurred in the system with which the writer is connected, may be of interest. One employee of the hydraulic department, shortly after a talk with his foreman on the desirability of collecting all tools at the end of the day, was found on the canal bank stripped, and about half drowned. It turned out that he had dropped into the water an old 35-cent lantern, and was diving for it in moving water nearly 20 ft. deep, and without the slightest indication of success. After receiving word from his superior that under the circumstances he would be forgiven for losing the lantern, he confided that " the old lamp was not good for much anyhow."

When changing some switch connections, one of the men, having completed his work, found he could not let go of the wrench which he still had on a nut on one of the high-tension switches. The inductive effect from 60 miles of parallel circuit was so great that the system had to be momentarily shut down to release him. The line knife-switches as above mentioned would have prevented this occurrence, which fortunately terminated wthout permanent injury.

A lineman working on a part of the system which has iron arms strapped together and grounded, happened to touch his foot to the private telephone wire while coming down the pole, some part of his body evidently touching the ground wire from the cross-arms. Both transmission lines above were dead, but over twenty miles away the telephone line ran on a pole line which was carrying 33,000 volts on its wires, and although the telephone line is from 7 to 25 ft. from the transmission wires this man's actions and yells indicated as he shouted out, " This dead wire ain't dead," that he was correct. The man's body belt saved him from a fall, and after regaining his nerve he descended the pole, taking care not to serve as a jumper between the ground wire and the telephone circuit. The ground wire at this time had not been covered by moulding, as the work was not quite completed. This incident is cited simply to indicate the tremendous inductive effects in high-tension work.

All water wheels should be inspected at regular periods, and they should be so designed as to be easily got at and defective parts renewed. There seems to be an inclination on the part of many station men to neglect the inspection of the interior of water wheels, but broken gate-vanes, worn gate-blocks, cracked rocker-arms, and loosened governor-rod connections are some of the troubles likely to be found, even in a semimonthly inspection. If the hydraulic cylinder operating the water-jacket intake gate is so constructed as to seat tight on the floor of its chamber it will stick. Sometimes two hours of continuous working of the four-way valve will be required to unseat the cylinder and raise the gate. This is a real calamity if it happens to occur at the time of an approaching peak of the load, when perhaps all units will be needed.

Wheel design does not cause all operating discomforts, for in the fall season of the year it is not an unusual thing to find as many as thirty to forty eels in a wheel-case, all of which, as far as can be discovered, have been bracing their backs up against the gate to prevent its closing. Many small eels and fish get ground up in the wheels, and there is always a period of several weeks each year when the stench of dead fish makes the inspection of the wheels anything but pleasant.

Spring brings slush-ice, which is perhaps the greatest of all evils, for it stops up the bucket-gate openings. A shutdown is the only relief; then the wheel-cases can be opened and the snow-ice melted out. The strain on the operator during a slush-ice run is greater than during a lightning storm, for although lightning effects are furious, there is an end to them, while an ice run may last several days, and never for a shorter period than several hours.

Sticks in the wheel-cases are at times causes of great alarm, on account of the noise occasioned by their beating against the iron water-jacket; but experience seems to indicate that the greater the noise the less the danger, for such a stick is too large to get between the guide-vanes, and is therefore not especially harmful. In all such cases, when the unit can be spared, it should be shut down and the wheel-case cleared.

Duplicate water-feeds for cooling the step-up transformers are a comfort to the operator, for even if a screen is placed at the intake, material will accumulate and require removal. A large feed which can be opened at the lower end and flushed out makes a good arrangement if duplicate feeds are undesirable.

A screen at the intake of the feed-mains is essential, and if it is placed in a glass section of pipe it is always visible. It should be placed so as to be quickly removed for cleaning.

It is a good feature to have the water discharge pipe from each transformer carry a glass section, or be actually broken, so that the amount of water being discharged may be seen.

When a step-up transformer needs repair it is quite a task to get the transformer oil out of and back into the case; this may be done quickly by gravity if a suitable receiving tank is provided underneath the floor, and a storage tank at some point above the transformer.

Care should be taken to have the water-wheel governor oil-pump of sufficient capacity to make the governor act quickly. A small pump-plunger will cause sufficient delay in starting up a unit to inconvenience the attendant in synchronizing.

It is well to keep the inside wiring of the private telephone line which runs on the transmission line well away from all other wiring and any metal work. Four feet of separation would seem sufficient, but on a number of occasions during lightning storms, current crept along a cement wall for four feet, thus forming an arc between the private line and the long-distance line. Where the long-distance line passed around a column, the current jumped through the insulation of the wiring to ground; this arc was maintained for quite a period. On account of this experience, the private and long-distance telephone circuits were brought in at different parts of the building, and all wiring kept entirely separated. No trouble between the circuits has been experienced since.

The solenoid equipments of the time-limit relays should be taken apart and cleaned at least three times a year, otherwise they become gummed with dust in spite of all possible protection, and thus their time-limit effect is very much increased. These relays should be tested at least once a month to see if they are acting in accordance with the indicated overload and time limit.

The oil-switch motors and connecting clutches require constant cleaning, but when painted or varnished care should be taken to confine the coating to its proper location.

An oil-switch failed to release upon the closing of the circuit on its motor, and an investigation proved that one of the attendants in his zeal to do a complete and sufficient job of painting, had painted the end of the solenoid rod; the rod stuck just enough so that the magnetic clutch failed to release. The result was certainly undesirable.

Three times when an oil-switch clutch has failed to release, so that the switch opened and closed consecutively several times, the voltage dropped from 110 to 65, and notwithstanding the fact that all sub-stations were carrying 60-cycle synchronous machines in the form of synchronous converters they were not sufficiently thrown out of step to drop out. This seems almost incredible when we consider that 10% variation is the desirable limit for this type of equipment.

In operating transmission lines in parallel, reverse-current relays on the receiving end will save many a complete interruption.

Static voltage detectors prove a great help to the operator, as they not only indicate that a phase wire is alive but in case the wire becomes grounded the disk of the device will stop revolving. This little and inexpensive equipment, therefore, can be made to serve in a very important and helpful manner.

The single-phase ammeters on the outgoing lines, when their transformers are connected immediately back of the step-up transformers, serve as a very positive ground indicator, for the operator will notice the amperage increasing on an outside grounded phase wire, and sometimes this warning will give him sufficient time to get the line in trouble cut out without in any way interfering with the service.

Line insulators, generally speaking, will stand very severe insulation strains, but it is not unusual for an insulator to become slightly defective, although the full development of the defect will cause no trouble until some time later. This fact was brought out quite clearly during the last lightning season when the number of insulators damaged on the 60 miles of transmission line was so small as to cause comment; but in September, when the lightning season was practically over, a very dense fog enveloped the system for more than 36 hours, causing the failure of some six or eight insulators. These insulators were distributed over the entire length of the system.

The good will of its neighbors is one of the best assets a transmission company can have, but it is unfortunate when their good intentions are thwarted, as was the case when one of our neighbors seeing the top of a wooden line pole on fire brought out a large pail of water and his best force pump, and attempted to put out the fire. His surprise and humiliation were great when he picked himself up from under his front-yard fence on the other side of the highway from the pole in question.

A paper presented at the 215th Meeting of the American Institute of Electrical Engineers, New York, March 1, 1907.

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ALTERNATING-CURRENT ELECTROLYSIS*

BY J. L. R. HAYDEN

A. CONTENTS

The development of the single-phase railway motor lead to the introduction of grounded alternating-current systems, in which the current is returned over the rail. With rail-return, necessarily more or less current strays through the ground, reaching gas and water pipes, lead cables, etc. When using direct current for railroading, lead cables, etc. are protected against electrolytic corrosion by connecting them to the negative terminal of the circuit, so that the stray current enters the cable from the ground, but does not leave it; that is, the cable is always at a negative potential against ground. With alternating currents this method of protection evidently is not feasible, since the potential difference constantly reverses.

An investigation was therefore undertaken to determine whether, and to what extent, alternating currents passing between any metallic conductor and the ground would produce electrolytic corrosion. These tests were started in the spring of 1906, and carried on practically continuously throughout most of the year.

These tests were extended to the investigation of different current-densities and different frequencies. First, several series of tests were made with diluted solutions of such salts as may be expected in the ground. Then different kinds of soils were investigated, and then tests made on a typical soil by adding different substances—carbonates, sulphates, organic matter, etc., and noting their effects. Ultimately, the possibility of protection against electrolytic corrosion was investigated.

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* In arranging this investigation, laying out the tests, and working up their results, and in recording them in the present paper, I am greatly indebted to Dr. Charles P. Steinmetz, in whose laboratory the investigation was made, and to the General Electric Co., which supplied the means and facilities for carrying out the work.

In the first sets of tests, lead and sheet-iron were investigated; in the last tests only lead plates were used, as the first tests proved the relative unimportance of iron.

B. METHOD OF TEST

Plates of 1.25-in. width and 2.5-in. height were used; that is, with about 6.25 square inch exposed area, of very thin and pure sheet-lead, so-called "test lead." These plates, after cleaning, were weighed on a chemical balance, reading accurately to about 0.5 milligrammes, then immersed in the electrolyte or the soil, the current passed through for a time varying from 60 hours to 390 hours; then the plates were taken out, washed with water and diluted acetic acid, (about 10%) dried, and again weighed. The total weight of the plate was about 6 grammes, and the amount dissolved usually several hundred milligrammes. Check tests showed that the amount of lead which can be dissolved chemically by acetic-acid washing does not exceed 1 or 2 milligrammes. The iron plates were cut to the same size, from transformer iron of 10 mils thickness, having an average weight of 2.5 grammes. They were treated in the same manner, except that very dilute hydrochloric acid was used for washing.

As containing vessels, glass tumblers were used of about 250-cu. cm. volume, and the soil was kept moist by replacing the evaporation with distilled water. A number of tumblers were connected in series with an alternating-current circuit, and immersed in a water bath. The same number of tumblers with similar contents but not connected to the electric circuit were immersed in the bath, and used as a check to determine the spontaneous corrosion due to chemical action of the soil.

As source of 60-cycle current were used the lighting mains of the City of Schenectady; as source of 25-cycle current, a small inverted single-phase converter changing from direct to alternating current; as source of direct current, a mercury-arc rectifier operated from the 60-cycle circuit.

To give quantitative values, all the results are expressed in percentage of direct-current electrolysis; that is, the amount

TABLE I.

MAY 1 TO JUNE 18, 1906. LEAD PLATES. 6.25 SQ. IN. SURFACE. 1% SALT SOLUTIONS.

Electrolyte	Frequency cycles	Current amperes	Duration of test hours	Milligrammes lead dissolved per hour			% direct-current electrolysis		Ratio of total corrosion to chemical corrosion	Ratio of current to frequency
				chemical	total	electrolysis	total	electrolysis		
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*
Ammonium Nitrate				2.18						
	60	0.3	60		3.14	0.96	0.271	0.084	1.44	5.0
		0.09	139		2.61	0.43	0.753	0.122	1.20	1.5
	25	0.3	150		10.65	8.47	0.918	0.737	4.88	12.0
		0.09	147		2.98	0.80	0.860	0.228	1.37	3.6
Ammonium Carbonate				0.102						
	60	0.3	60		2.14	2.04	0.184	0.176	21.0	5.0
		0.09	139		0.41	0.31	0.118	0.088	4.0	1.5
	25	0.3	150		6.70	6.60	0.578	0.570	65.8	12.0
		0.09	147		0.83	0.73	0.240	0.210	8.2	3.6
Sodium-Potassium Nitrate				0.553						
	60	0.3	63		5.05	4.50	0.436	0.390	9.15	5.0
		0.09	140		1.90	1.35	0.547	0.392	3.43	1.5
	25	0.3	150		7.57	7.02	0.653	0.607	13.70	12.0
		0.09	149		2.66	2.11	0.765	0.610	4.82	3.6
Sodium Potassium Carbonate				0.535						
	60	0.3	77		0.73	0.20	0.063	0.017	1.37	5.0
		0.09	140		0.54	0.005	0.156	0.001	1.01	1.5
	25	0.3	150		0.67	0.14	0.058	0.012	1.25	12.0
		0.09	147		0.37	—0.16	0.107	—0.046	0.69	3.6
Sodium-Potassium Chloride				0.270						
	60	0.3	78		1.42	1.15	0.122	0.097	5.26	5.0
		0.09	140		1.08	0.81	0.312	0.234	4.00	1.5
	25	0.3	150		1.46	1.19	0.126	0.103	5.41	12.0
		0.09	147		1.09	0.82	0.314	0.234	4.03	3.6
Sodium-Potassium Sulphate				0.316						
	60	0.3	79		0.75	0.43	0.065	0.037	2.38	5.0
		0.09	140		0.595	0.28	0.172	0.079	1.88	1.5
	25	0.3	150		0.92	0.60	0.079	0.052	2.92	12.0
		0.09	147		0.65	0.33	0.187	0.095	2.06	3.6
Mixture				0.170						
	60	0.3	79		4.54	4.37	0.392	0.377	26.7	5.0
		0.09	140		1.35	1.18	0.390	0.338	7.9	[illegible]
	25	0.3	150		3.14	2.97	0.271	0.257	18.5	[illegible]
		0.09	147		1.58	1.41	0.455	0.408	9.3	3.6

TABLE II

May 1 to June 18, 1906. Iron Plates. 6.25 Sq. In. Surface. 1% Salt Solutions.

Electrolyte	Frequency cycles	Current amperes	Duration of test hours	Milligrammes lead dissolved per hour			% direct-current electrolysis		Ratio of total corrosion to chemical corrosion	Ratio of current to frequency
				chemical	total	electrolysis	total	electrolysis		
a	b	c	d	e	f	g	h	i	j	k
Ammonium Nitrate				1.841						
	60	0.3	63		3.77	1.93	1.21	0.62	2.05	5.0
		0.09	162		2.76	0.92	2.96	0.99	1.50	1.5
	25	0.3	143		3.66	1.82	1.18	0.586	1.99	12.0
		0.09	145		2.66	0.82	2.85	0.88	1.44	3.6
Ammonium Carbonate				0.						
	60	0.3	63		0.50	0.50	0.161	0.161		
		0.09	162		0.	0.	0.	0.		
	25	0.3	143		0.017	0.017	0.005	0.005		
		0.09	145		0.	0.	0.	0.		
Sodium-Potassium Nitrate				0.220						
	60	0.3	66		0.570	0.350	0.184	0.113	2.59	5.0
		0.09	162		0.283	0.063	0.304	0.068	1.29	1.5
	25	0.3	143		0.613	0.393	0.197	0.126	2.78	12.0
		0.09	145		0.462	0.242	0.496	0.260	2.10	3.6
Sodium-Potassium Carbonate				0.						
	60	0.3	68		0.	0.	0.	0.		
		0.09	162		0.	0.	0.	0.		
	25	0.3	143		0.007	0.007	0.002	0.002		
		0.09	145		0.014	0.014	0.015	0.015		
Sodium-Potassium Chloride				0.299						
	60	0.3	69		0.59	0.290	0.190	0.093	1.97	5.0
		0.09	163		0.307	0.008	0.330	0.009	1.03	1.5
	25	0.3	143		0.606	0.307	0.195	0.099	2.02	12.0
		0.09	145		0.439	0.140	0.471	0.150	1.47	3.6
Sodium-Potassium Sulphate				0.371						
	60	0.3	70		0.415	0.044	0.134	0.014	1.12	5.0
		0.09	163							
	25	0.3	143		0.644	0.273	0.207	0.088	1.73	12.0
		0.09	145							
Mixture				0.787						
	60	0.3	71		0.97	0.183	0.312	0.059	1.23	5.0
		0.09	163							
	25	0.3	143							
		0.09	145							

of metal dissolved per ampere-hour by alternating-current electrolysis is given in terms of the amount which 1 ampere-hour direct current should dissolve by Faraday's law: 3.86 grammes lead and 1.035 grammes iron per ampere-hour, assuming the valency of both metals as 2. In some tests, plates of one-half or one-quarter of these sizes were also used, in series with full-size plates, to determine the effect of various current-densities.

C. Tests With Salt Solutions

One per cent. solutions in distilled water were used of those salts which may be expected in the soil.

1. 1% ammonium nitrate.
2. 1% " carbonate.
3. 0.5% sodium nitrate and 0.5% potassium nitrate.
4. 0.5% " carbonate and 0.5% " carbonate.
5. 0.5% " chloride and 0.5% " chloride.
6. 0.5% " sulphate and 0.5% " sulphate.
7. 0.25% ammonium nitrate, 0.25% ammonium carbonate,
0.125% sodium chloride, 0.125% potassium chloride,
0.125% sodium sulphate, 0.125% potassium sulphate,

referred to in the following as "mixture."

Eight sets of tests were made; four with lead plates and four with iron plates, under the following conditions:

a. 60 cycles 0.3 amperes, or 0.048 amperes per square inch
b. 60 " 0.09 " " 0.0144 " " " "
c. 25 " 0.3 " " 0.048 " " " "
d. 25 " 0.09 " " 0.0144 " " " "

It is interesting to note that considerable quantities of lead were found in solution only with ammonium nitrate, and small traces of lead with sodium-potassium carbonate. No lead went into solution with the other salts.

The results of the four sets of tests made with lead plates are given in Table I; the results of the tests with iron plates in Table II.

As indicated by Tables I and II, the electrolytic corrosion due to alternating current is very small compared with the electrolytic effect due to direct current, as shown by columns *h* and *i*; in no case did it equal 1%, in fact it rarely exceeded ½% of the direct-current electrolysis.

In general, then, iron is attacked less than lead. It therefore seems that, in general, with iron, alternating-current electrolysis is less to be feared, except in extreme cases; that is, with large currents passing between rails and iron pipes. With lead cables, the amount of corrosion indicated by Table I, would in many cases lead to a rapid destruction of the relatively thin cable sheet. The effect of alternating current on lead cables is therefore the more serious problem.

As shown in Table I, no general relation exists between the chemical corrosion, column *e*; that is the corrosion taking place without any current, and the electrical corrosion, column *i*, resulting from the passage of an alternating current. For instance, the chemical corrosion is about the same with sodium-potassium nitrate as with carbonate solutions; while the electrical corrosion is very high with nitrates, and practically neglible with carbonates.

TABLE III.

LEAD PLATES.

Electrolyte	Chemical corrosion mg. per hour	Total Corrosion % direct-current electrolysis			Electrical Corrosion % direct-current electrolysis		
		25	60	avg.	25	60	avg.
a. ammonium nitrate	2.18	0.889	0.512	0.700	0.483	0.103	0.293
b. ammonium carbonate	0.102	0.409	0.151	0.280	0.390	0.132	0.261
sodium potassium nitrate	0.553	0.709	0.491	0.600	0.608	0.391	0.500
" " carbonate	0.535	0.083	0.110	0.096	0.017	0.009	0.004
c. " " chloride	0.270	0.220	0.217	0.218	0.169	0.166	0.167
d. " " sulphate	0.316	0.133	0.119	0.126	0.074	0.058	0.066
Mixture	0.170	0.363	0.391	0.377	0.333	0.358	0.345
Avg. of *a, b, c, d*	0.717	0.413	0.250	0.331	0.279	0.115	0.197

Ammonium nitrate: large quantities of lead in solution.
Sodium potassium carbonate: traces of lead in solution.
Ammonium carbonate: very small traces of lead in solution in chemical, but none in electrolytic corrosion.
All others, including sodium potassium nitrate and chlorides: no traces of lead in solution

High current densities sometimes increase the electrical corrosion, as with ammonium salts, sometimes it decreases the corrosion, as with chlorides; but usually the current density has no appreciable effect.

In general, electrolytic corrosion is greater at lower frequency, but this is not always the case. For instance, with carbonates, where the electrolytic action is very low, high frequency seems to corrode more than low frequency; but with alkali nitrates, chlorides, and the mixture of salts, frequency has no appreciable effect.

Interesting is the comparison of the last two columns, *j*, the ratio of the total corrosion to the chemical corrosion, and *k*, the ratio of current to frequency; that is, the electric quantity per half wave. In most cases these two columns correspond closely; that is, the higher the quantity of electricity per alternation the greater the corrosion.

To investigate these relations still further, Table III gives the average values of corrosion, chemical, electrical, and total for 25 cycles and for 60 cycles. Table IV gives the average values for high- and for low-current densities, and their averages.

In the last row of these tables is given the corrosion which should be expected from the mixture, calculated as average of the corrosion due to its components. As seen, the mixture of different salts gives a very much lower chemical attack than the average attack of the components; that is, some salts, as the sulphates or carbonates, protect the lead against the attack by the nitrates. Electrolytically, however, the reverse is the case; this protective action of one salt against the attack by another does not seem to exist.

TABLE IV.

LEAD PLATES.

Electrolyte	Chemical corrosion mg. per hour	Total Corrosion % direct-current electrolysis			Electrical Corrosion % direct-current electrolysis		
		0.3 amp.	.09 amp.	avg.	0.3 amp.	.09 amp.	avg.
a. ammonium nitrate	2.18	0.595	0.806	0.700	0.410	0.175	0.293
b. ammonium carbonate	0.102	0.381	0.179	0.280	0.373	0.149	0.261
sodium potassium nitrate	0.553	0.545	0.656	0.600	0.498	0.501	0.500
" " carbonate	0.535	0.061	0.131	0.096	0.014	0.022	0.004
c. " " chloride	0.0270	0.124	0.313	0.218	0.100	0.234	0.167
d. " " sulphate	.0316	0.072	0.180	0.126	0.045	0.087	0.066
Mixture	0.170	0.332	0.422	0.377	0.317	0.373	0.345
Avg. of *a*, *b*, *c*, *d*	0.717	0.293	0.369	0.331	0.232	0.161	0.197

The conclusion herefrom is, that it may be possible to protect lead cables chemically against spontaneous or chemical corrosion by surrounding the cables with alkali sulphates, for instance, but this affords no appreciable protection against electrolytic action by alternating current.

In Table I, the data on the electrical corrosion by ammonium nitrate are not very reliable, since ammonium nitrate attacks and dissolves lead chemically so rapidly that the additional attack by the alternating current cannot be determined accurately. In all other cases, the chemical corrosion is rather less than the electrical.

TABLE V.

LEAD PLATES—ORDER OF CHEMICAL CORROSION

	mg. per hour
1. Ammonium nitrate	2.18
2. Sodium-potassium nitrate	0.553
3. Sodium-potassium carbonate	0.535
4. Sodium-potassium sulphate	0.316
5. Sodium-potassium chloride	0.270
6. Mixture	0.170
7. Ammonium carbonate	0.102

Table V, gives the order in which lead is attacked chemically by the different solutions. Nitrates attack the hardest, next come the alkali carbonates, and last is ammonium carbonate, and the mixture of salts, in which some salts act as a protection against the others.

TABLE VI.

LEAD PLATES. ORDER OF ALTERNATING-CURRENT ELECTROLYTIC CORROSION

Total Corrosion					Electrical Corrosion				
Cycles		Amperes		Average	Cycles		Amperes		Average
25	60	0.3	0.09		25	60	0.3	0.09	
1	1	1	1	1	2	2	2	2	2
2	2	2	2	2	1	6	1	6	6
7	6	7	6	6	7	5	7	5	1
6	5	6	5	7	6	7	6	1	7
5	7	5	4, 7	5	5	1	5	7	5
4	4	4		4	4	4	4	4	4
3	3	3	3	3	3	3	3	3	3

Table VI gives the order of attack by alternating current, the total corrosion, and the electrical corrosion. The different solutions are given by their numbers in Table V; that is, the numbers in Table VI represent the order of chemical corrosion.

As seen, the nitrates give the greatest corrosion, chemically as well as electrically. The other salts act electrically practically in reverse order to their action chemically: the alkali carbonates give the greatest chemical and the least electrical attack, next come the sulphates, then the chlorides.

TABLE VII

Lead Plates—Order of Total Corrosion

		% direct-current electrolysis	
	Number:	Total:	Electrical
Ammonium nitrate and sodium-potassium nitrate	1,2	0.650	0.397
Mixture, and ammonium carbonate	6,7	0.329	0.303
Sodium-potassium chloride	5	0.218	0.167
Sodium-potassium sulphate	4	0.126	0.066
Sodium-potassium carbonate	3	0.096	0

The approximate order of electrical corrosion of the different solutions is given in Table VII. Comparing Table VII with Table V, it is evident that, with the exception of ammonium nitrate and sodium-potassium nitrate, the order of attack is reversed.

TABLE VIII.

Lead Plates. Ratios.

Solution	Net corrosion, by current only					
	$\frac{\text{Low}}{\text{high}}$ frequency			$\frac{\text{High}}{\text{low}}$ current		
	0.3 amp.	0.09 amp.	avg.	25	60	avg.
1. Ammonium nitrate	8.77	1.87	4.69	3.23	.69	2.34
2. Ammonium carbonate	3.23	2.38	2.95	2.71	2.00	2.51
3. Sodium potassium nitrate	1.56	1.56	1.56	0.995	0.995	0.995
4. " " carbonate						
5. " " chloride	1.06	1.00	1.02	0.435	0.41	0.427
6. " " sulphate	1.41	1.20	1.28	0.55	0.47	0.517
7. Mixture	0.68	1.21	0.93	0.63	1.11	0.848
8. Avg. of 1, 2, 5, 6			2.43			1.44

Table VIII gives the ratio of electrical corrosion at low frequency to that at high frequency, and the ratio of corrosion at high current-density to that at low current-density; that is, gives the effect of frequency, and of current-density.

ORDER OF RATIOS

Frequency ratio: high current	1	2	3	6	5	7
low "	2	1	3	7	6	5
average "	1	2	3	6	5	7
Current ratio: low frequency	1	2	3	7	6	5
high "	2	7	3	1	6	5
average "	2	1	3	7	6	5
Total average	2	1	3	7	6	5

Or, order of ratio: $\frac{\text{low}}{\text{high}}$ frequency, or $\frac{\text{high}}{\text{low}}$ current, that is, $\frac{\text{high}}{\text{low}}$ quantity of electricity per half wave:

Ammonium nitrate and carbonate.
Sodium-potassium nitrate.
Sodium-potassium sulphate, and mixture.
Sodium-potassium chloride.

As seen, the effect of frequency varies from 4.69 with ammonium nitrate to 0.93 with the mixture, and the effect of current density from 2.51 with ammonium carbonate, to 0.427 with alkali chlorides. In general, then, the order of salts in the two cases is similar; that is, decreasing frequency and increasing current-density have similar effects.

These tables show, however, that the effects of frequency and of current-density depend very largely on the chemical constitution. Ammonium salts show a very great increase of corrosion with increasing current-density, or decreasing frequency; whereas chlorides and sulphates show little effects of frequency, and a decrease of corrosion with increasing current-density. In general, the conclusions of the tests with lead plates in salt solutions are:

1. Chemical as well as electrical corrosion is greatest with nitrates. With other salts or mixtures of salts, the electrical corrosion is not proportional to the chemical corrosion, but, with the salts investigated, rather inversely proportional thereto; that is, where the chemical attack is considerable, the electrical action is more completely reversible than with a chemically less active electrolyte.

2. Current-density in general has no decided effect. High current-density increases the attack with some compounds, as ammonium salts, and decreases it with others, as chlorides and sulphates, provided the current density is not so high as to give

an appreciable increase of temperature, which then increases the corrosion.

3. Low frequency usually attacks more than high frequency. But the increase of corrosion due to lower frequency, entirely depends on chemical constitution, being largest with ammonium salts, and practically negligible with chlorides and sulphates.

4. Mixtures of salts frequently give a greatly reduced chemical corrosion, but give about the same or a higher electrical corrosion than their components; that is, chemical protection fails to protect electrolytically.

5. Iron is less attacked than lead, and is practically not attacked at all by carbonates.

D. EXPERIMENTS WITH DIFFERENT SOILS

Tests were made with different soils.

1. Garden soil, a clay loam, taken from Dr. Steinmetz's garden.

2. Street mud, collected from the surface of Schenectady's main street (State Street railway crossing), where the New York Central Railroad crosses the trolley line, and thus containing the accumulated effect of foot, horse, electric, and steam traffic.

3. Sub-soil, a sandy soil collected from below the street surface in the older part of Schenectady, where people lived for over 200 years, the soil containing the seepage of centuries.

4. A mixture, in equal volume, of these three soils.

The soil was kept moist by replacing evaporation with distilled water. It was considered that these three soils are about representatives of the more severe conditions to which lead pipes and cables in the soil are exposed. Four sets of tests were made, of lead plates, and of iron plates, with 60 cycles and with 25 cycles, all at one-tenth ampere current. The same size of plate was used as before and tested in the same manner. The results of these tests are abstacted in Table IX.

Very marked, however, is the effect of frequency. While at 60 cycles the electrical corrosion is very small, averaging less than 0.05% with lead plates, it is quite considerable at 25 cycles, averaging 0.222%.

The chemical corrosion of lead plates averages 0.148 milligrammes per hour, with 6.25 square inch plate surface. The total corrosion averages 0.085% at 60 cycles, and 0.216% at 25 cycles, and the electrical corrosion averages 0.047% at 60 cycles and 0.22% at 25 cycles. Especially marked is the enormous increase of corrosion with increase of temperature, which is investigated later.

Comparing the relatively small differences found in Table IX for different soils, with the great variations in the attack due to different salt solutions, in Table I and II, it was thought sufficient in the further investigations to use only one form of soil as typical—the mixture referred to above, but to investigate the effect of the addition of different substances.

TABLE IX.

JUNE 21 TO JULY 17, 1906. TESTS WITH DIFFERENT SOILS.

Plates, 6.25 sq. in. total surface; 0.1 ampere.

Electrolyte	Frequency cycles	Dur. of test	milligrammes dissolved per hour			% direct-current electrolysis	
		hours	chem.	total	elec.	total	elec.
a	*b*	*c*	*e*	*f*	*g*	*h*	*i*
Lead Plates.							
Garden soil	60	254	0.115	0.227	0.112	0.059	0.029
	25	244		0.908	0.793	0.235	0.205
Street mud	60	254	0.130	0.311	0.181	0.081	0.047
	25	244		1.250	1.120	0.324	0.290
Sub-soil*	60	254	0.224	0.462	0.238	0.120	0.062
	25	244		0.642	0.418	0.167	0.108
Mixture	60	254	0.121	0.310	0.189	0.080	0.049
	25	244		1.221	1.100	0.317	0.285
Iron Plates.							
Garden soil	60	254	0.078	0.169	0.091	0.163	0.088
	25	244		0.252	0.174	0.243	0.168
Street mud	60	254	0.036	0.099	0.063	0.095	0.061
	25	244		0.159	0.123	0.154	0.119
Sub-soil*	60	254	0.092	0.98	0.89	0.945	0.86
	25	244		1.99	1.90	1.93	1.83
Mixture	60	254	0.044	0.092	0.048	0.089	0.046
	25	244		0.087	0.043	0.084	0.042

* Appreciable rise of temperature by $I^2 r$.

E. SALT SOLUTIONS IN SOIL

Tests were therefore made by moistening the soil, not as before with distilled water, but with very diluted solutions of nitrates, and nitrites, carbonates, sulphates, and their mixture, to determine whether the presence of nitrates increases the corrosion, and the presence of carbonates or sulphates exerts a protective action. These experiments were made only at 25 cycles, 0.1 ampere, with the same size of lead and iron plates, of 6.25 square inch total surface, and are abstracted in Table X and XI.

The following solutions were used.

1. City water, (Schenectady) containing appreciable quantities of bicarbonate of calcium.

2. Solution of 0.1% potassium carbonate and 0.1% sodium carbonate in distilled water, a total of 0.2%.

3. Solution of 0.1% potassium sulphate and 0.1% sodium sulphate, in distilled water, a total of 0.2%.

TABLE X.

JULY 23 TO AUGUST 3, 1906. MIXED SOIL AND SALT SOLUTIONS.

25 cycles, 0.1 ampere, 6.25 sq. in. total plate surface.
Duration of test, 219.5 hours.
Mean temperature of water bath, 23.7° cent.

Electrolyte	Milligrammes dissolved per hour			% direct-current electrolysis	
	chem.	total	elec.	total	elec.
a	*e*	*f*	*g*	*h*	*i*
Lead Plates.					
City water	0.106	0.851	0.745	0.221	0.194
Potassium sodium carbonate	0.104	0.304	0.200	0.079	0.052
Nitrates and nitrites	0.166	0.716	0.550	0.186	0.143
Carbonates, nitrates and nitrites	0.128	0.481	0.353	0.125	0.092
Iron Plates.					
City water	0.073	0.262	0.189	0.253	0.183
Potassium sodium carbonates	0.117	0.288	0.171	0.278	0.165
Nitrates and nitrites	0.100	0.203	0.103	0.196	0.100
Carbonates, nitrates and nitrites	0.112	0.365	0.253	0.353	0.245

4. Solution of 0.1% ammonium nitrate, 0.05% potassium nitrite, and 0.05% sodium nitrite in distilled water, a total of 0.2%.

5. Solution of 0.1% potassium carbonate, 0.1% sodium carbonate, 0.1% ammonium nitrate, 0.05% potassium nitrite, 0.05% sodium nitrite, a total of 0.4%.

6. Solution of 0.1% potassium sulphate, 0.1% sodium sulphate, 0.1% ammonium nitrate, 0.05% potassium nitrite, 0.05% sodium nitrite, a total of 0.4%.

A comparison of Tables X and XI well illustrates the erratic character of the phenomenon of alternating-current electrolysis.

These two tests were made immediately after each other, under as nearly identical conditions as possible; the same frequency, current-density, etc., the same kind of soil, and practically the same temperatures. The chemical corrosion in both tests is about the same. In the second test it is somewhat less with lead plates, and somewhat more with iron plates, than in the first test. Wide differences are found in the electrical corrosion, not only in the numerical values, but also in the character of the effect produced by the different electrolytes.

In the first test, nitrates and nitrites exert a marked protective action on iron plates, which, however, disappears in the presence of carbonates. In the second test, nitrates and nitrites greatly increase the corrosion of iron plates. This may have something to do with the possibility of a passive state of the iron, and needs further investigation.

TABLE XI.

August 7 to 23, 1906. Mixed Soil and Salt Solution.

25 cycles, 0.1 amperes, 6.25 sq. in. total plate surface.
Duration of test, 333.5 hours.
Mean temperature of water bath, 22.3° cent.

Electrolyte	Milligrammes dissolved per hour			% direct-current electrolysis	
	chem.	total	elec.	total	elec.
a	*e*	*f*	*g*	*h*	*i*
Lead Plates.					
City water	0.085	1.160	1.075	0.300	0.278
Sulphates	0.073	0.505	0.432	0.131	0.112
Nitrates and nitrites	0.101	1.911	1.810	0.495	0.469
Sulphates, nitrates and nitrites	0.108	2.048	1.94	0.530	0.503
Iron Plates.					
City water	0.102	0.212	0.110	0.204	0.107
Sulphates	0.145	0.370	0.225	0.357	0.217
Nitrates and nitrites	0.158	0.483	0.325	0.466	0.313
Sulphates, nitrates and nitrites	0.155	0.642	0.487	0.618	0.469

Carbonates exert a marked protective action on lead plates, which is reduced if nitrates and nitrites are present; even then it is considerable. Sulphates also exert a protective effect on lead plates, but this protective action disappears, and the corrosion is increased in the presence of nitrates and nitrites. This agrees with previous experience in the tests with salt solutions. With iron plates, sulphates increase the corrosion.

It seems then that a certain protective action against alternating-current electrolysis of lead plates is exerted by carbonates and by sulphates. Since alkali salts are excluded from practical use by their solubility, a series of tests was undertaken to determine the effect that calcium carbonate and sulphate—chalk and gypsum—have on alternating-current electrolytic corrosion, when mixing these salts with the soil surrounding the lead cables.

F. CALCIUM SALTS IN SOIL

Tests were made on the effect produced by mixing 5% chalk or 5% gypsum, or both, with the soil used in alternating-current electrolysis. Some tests were also made by adding 5% Portland cement, and by adding 5% fertilizer, containing nitrates, phosphates, and ammonium compounds. Only lead plates were used, of the standard size of 1.25 in. by 2.25 in., with a current of 0.1 ampere.

TABLE XII.
AUGUST 25 TO SEPT. 9, 1906. LEAD PLATES.

25 cycles, 0.1 ampere, 6.25 sq. in. total plate surface.
Duration of test, 362 hours.
Mean temperature of water bath, 23.1° cent.

Electrolyte Solid *a*	 Liquid	Milligrammes dissolved per hour chem. *e*	 total *f*	 elec. *g*	% direct-current electrolysis total *h*	 elec. *i*
Mixed soil.	City water.....	0.116	1.256	1.140	0.326	0.296
Mixed soil.	Salt solution*..	0.117	0.794	0.677	0.206	0.176
Mixed soil. +5% Chalk. + 5% Gypsum	City Water.....	0.079	0.245	0.166	0.0635	0.043
Mixed soil. + 5% Chalk. + 5% Gypsum.	Salt solution*..	0.126	0.704	0.578	0.182	0.150

* 0.5% solution of mixed potassium, sodium, ammonium, nitrates, nitrites, chlorides, as described above.

Tests were made at 60 cycles, as well as at 25 cycles, to determine the effect of frequency. Some tests were made with plates of half and quarter size, in series with full-size plates, to determine the effect of current-density. The 60-cycle and 25-cycle tests, and the tests with full-, half-, and quarter-size plates, were made simultaneoutly, with the tumblers immersed in the same water bath so as to have the same temperature in all these tests.

Tests were made with the mixed soil, and also with the same soil by adding: 5% chalk, 5% gypsum, 5% Portland cement, 5% fertilizer: containing nitrates, phosphates, ammonia, 5% fertilizer, 5% chalk, and 5% gypsum. City water was used as liquid, except in a few tests, in which 0.5% salt solution was used, of the following constitution: ammonium nitrate 2, potassium nitrite 1, sodium nitrite 1, potassium chloride 1, sodium chloride 1, water 1194. Each tumbler contained about 120 cu. cm. of liquid, in addition to the soil.

TABLE XIII.

SEPT. 17 TO OCT. 3, 1906. LEAD PLATES.

0.1 ampere, 6.25 sq. in. total plate surface, half and quarter thereof.
Mean temperature of water bath, 22.7° cent. and 19.5° cent. respectively.
Liquid: City Water.

Electrolyte 22.7° cent. *a*	Frequency cycles *b*	Duration of test, hours *d*	Milligrammes dissolved per hour			% direct-current electrolysis		Ratio of attack 25–60 *l*
			chem. *e*	total *f*	elec. *g*	total *h*	elec. *i*	
Mixed soil	25	277	0.159	1.451	1.292	0.376	0.335	
	60	306		0.996	0.837	0.258	0.217	1.54
Mixed soil + 5% chalk	25	277	0.155	1.088	0.933	0.282	0.242	
	60	306		0.711	0.556	0.184	0.144	1.68
Mixed soil + 5% gypsum	25	277	0.180	1.843	0.663	0.478	0.431	
	60	306		0.435	0.255	0.113	0.066	6.53
Mixed soil + 5% chalk + 5% gypsum	25	277	0.134	1.544	1.410	0.400	0.365	
	60	306		0.499	0.365	0.129	0.095	3.84
Mixed soil + 5% Portland cement	25	277	0.247	0.485	0.238	0.125	0.062	
	60	306		0.512	1.265	0.132	0.068	0.91
19.5° cent.								
Mixed soil + 5% fertilizer	25	217	0.301	2.481	2.180	0.642	0.565	1.86
	60	234		1.474	1.173	0.383	0.304	
Mixed soil + 5% fertilizer + 5% chalk + 5% gypsum	25	217	0.303	3.638	3.335	0.940	0.864	
	60	234		2.483	2.180	0.643	0.564	1.53
Mixed soil, ½ size plates	25	217	0.162	1.289	1.127	0.334	0.292	
	60	234		1.119	0.957	0.290	0.247	1.18
Mixed soil, ¼ size plates	25	217	0.064	1.839	1.775*	0.476	0.460	
	60	234						

* Lead plates eaten to pieces. The pieces were collected as far as possible, but no doubt some escaped, hence this value is probably somewhat too large.

The three sets of tests are given in Tables XI, XII and XIII.

Table XII seems to show that the very diluted salt solution rather reduces the electrolytic corrosion.

The addition of chalk and gypsum to the soil exerts a marked protective action, which, however, practically disappears when a mixed salt solution is used instead of water.

Table XIII shows a moderate protective action against electrolytic corrosion, exerted by the addition of chalk to the soil.

Gypsum exerts a marked protective action only at 60 cycles, but increases the corrosion at 25 cycles.

Addition of chalk, as well as gypsum, gives the same effect as gypsum: a reduction of the corrosion at 60 cycles, but an increase at 25 cycles.

Organic materials, as fertilizer, greatly increase the electrolytic corrosion, and the addition of chalk and gypsum in this case still further increases the corrosion.

The effect of Portland cement is interesting: while the chemical corrosion is greatly increased by cement, from 0.159 to 0.247 milligrammes per hour, the electrolytic corrosion is greatly reduced and becomes very small at either frequency.

The current-density seems to have very little, if any, effect, since half-size plates, with the same current, give practically the same corrosion as full-size plates.

Especially interesting is the effect of frequency. In general, at lower frequency the corrosion is greater; but the order in which it varies with the frequency very largely depends on the chemical character of the soil. With soil only, the corrosion increases with decreasing frequency, but not any where near inversely proportional to the frequency. The addition of chalk or fertilizer seems slightly to increase the effect of frequency, but not to any great extent. Gypsum very greatly increases it, so that 60-cycle electrolysis nearly disappears, and the 25-cycle electrolysis is more than six times the 60-cycle electrolysis. Inversely, cement reduces the effect of frequency, so that both frequencies give practically the same attack.

It is worth noting the high values of electrolytic corrosion observed in soils containing fertilizer, especially when chalk and gypsum are added. These reach nearly 1% of direct-current corrosion at 25 cycles, and exceed one-half per cent at 60 cycles.

G. CONCLUSIONS

From the data recorded in Tables IX to XII, a number of comparisons on the effect of different constituents in the soil can be made. These are given in Tables XIV, XV, and XVI.

In these tables, the relative values of chemical, total, and electrical corrosion are given.

Table XIV. Effect of nitrates, nitrites, and similar compounds, as fertilizer. The corrosion is considerably increased, the chemical corrosion in all cases, the electrical corrosion in most tests, by an average of about 60%.

TABLE XIV.

Effect of Nitrates, nitrates and fertilizer:	Table No.	Frequency cycles	Corrosion : relative		
			chem.	total	elec.
Mixed soil only			1	1	1
Alkali nitrates and nitrites	X	25	1.56	0.84	0.74
Alkali nitrates and nitrites	XI	25	1.19	[illegible]	1.69
Alkali nitrates, nitrites and carbonate	X	25	1.21	0.57	0.48
Alkali nitrates, nitrites and sulphate	XI	25	1.27	1.77	1.81
Fertilizer	XIII	25	1.90	1.71	1.68
Fertilizer	XIII	60	1.90	1.48	1.40
Fertilizer and chalk and gypsum	XIII	25	1.91	2.50	2.57
	XIII	60	1.91	2.49	2.60
Average			1.61	1.63	1.62

TABLE XV.

Effect of carbonates, etc.	Table No.	Frequency cycles	Corrosion; relative		
			chem.	total	elec.
Mixed soil only			1	1	1
Alkali carbonates	X	25	0.98	0.36	0.27
Chalk	XIII	25	0.97	0.75	0.72
Chalk	XIII	60	0.97	0.71	0.66
Portland cement	XIII	25	1.56	0.33	0.19
Portland cement	XIII	60	1.56	0.51	0.31
Mixed soil containing gypsum			1	1	1
Chalk	XIII	25	0.75	0.84	0.85
Chalk	XIII	60	0.75	1.14*	1.14*
Mixed soil containing nitrates or fertilizer			1	1	1
Alkali carbonates	X	25	0.77	0.67	0.64
Chalk and gypsum	XIII	25	1.01	1.46	1.53
Chalk and gypsum	XIII	60	1.01	1.68	1.85

* Ratios of two small values, therefore less reliable.

The presence of nitrates, fertilizers etc., in the soil is therefore objectionable.

Table XV. Effect of carbonates, and, in general, alkaline compounds.

Carbonates and alkaline compounds, as far as observed, always reduce the electrolytic corrosion of lead, and also the chemical corrosion; that is, they exert a protective action. This is most pronounced with alkali carbonates and cement, the latter, however, greatly increasing the chemical corrosion.

The protective action of carbonates seems to decrease in the presence of sulphates, nitrates, etc., and is in general not sufficiently large to give promise of a method of chemically protecting lead plates against alternating-current electrolysis, by surrounding them with calcium carbonate or hydrate.

Table XVI. Effect of sulphates. Sulphates sometime exert a protecting action, but sometime increase the corrosion. The latter seems to be the case in the presence of nitrates.

TABLE XVI.

	Table No.	Frequency cycles	Corrosion; relative		
Effect of sulphates, etc.			chem.	total	elec.
Mixed soil only			1	1	1
Alkali sulphates	XI	25	0.86	0.44	0.40
Gypsum	XIII	25	1.13	1.27	1.29
Gypsum	XIII	60	1.13	0.44	0.30
Chalk and gypsum	XII	25	0.68	0.20	0.15
Chalk and gypsum	XIII	25	0.84	1.07	1.09
Chalk and gypsum	XIII	60	0.84	0.50	0.44
Mixed soil containing nitrates or fertilizer			1	1	1
Alkali sulphates	XI	25	1.07	1.07	1.07
Chalk and gypsum	XIII	25	1.01	1.46	1.53
Gypsum	XIII	60	1.01	1.68	1.85

In Table XVII are calculated the tests made with soil only, without additional protective or destructive compounds. These give an average spontaneous or chemical corrosion of 0.117 milligrammes per hour, or 0.0188 milligrammes per hour and square inch plate surface, and an average total corrosion, at 25 cycles, of 0.312%, or an electrical corrosion of 0.280% of direct-current electrolysis.

Assuming the specific gravity of lead as 11.4, under these conditions, by chemical corrosion, in 10 years a layer of lead of 0.009 in. thick would be consumed. That is, under average conditions, chemical corrosion of lead cables could be neglected.

Electrically, at a current-density of 1 ampere per square foot, 25 cycles would, in 10 years, destroy an additional layer of lead 0.07 in. thick. In the worst case observed this would increase to 0.22 in. or nearly one-quarter inch; that is, would eat through the cable armor long before this time.

With a current-density of 10 amperes per square foot, a cable armor $\frac{1}{8}$ in. thick would in average be eaten through in 1.8 years, but in the extreme case may be eaten through in 0.57 years, or 7 months.

H. EFFECT OF TEMPERATURE

Since in the preceding tests, especially in the first set of tests, before a water bath was used, it was noticed that the values of alternating-current electrolytic corrosion were high, whenever the temperature of the cell is increased by its $I^2 R$ loss, some tests were made on the effect of temperature by heating the water bath in which the cells were immersed. The temperature of the bath fluctuated between 36° and 42° cent. with an average of 39.5° cent.

TABLE XVII.
LEAD PLATES. MIXED SOIL. 25 CYCLES.

	Corrosion:		
	chemical	total	electrical
Table No.	Milligrammes per hour	% direct-current electrolysis	
IX........	0.121	0.317	0.285
X.........	0.106	0.221	0.194
XI........	0.085	0.300	0.278
XII.......	0.116	0.326	0.296
XIII......	0.159	0.376	0.335
XIII......	½ size	0.334	0.292
Average...	0.117	0.312	0.280
Maximum corrosion observed..	0.303	0.940	0.864

Tests were made with mixed soil, and with mixed soil and 5% fertilizer added, at 0.1 ampere, 25 cycles, and without current, and gave the results recorded in Table XVIII.

As seen from Table XIX, and comparing these results with the average values of previous experiments, the chemical as well as the electrolytic corrosion is very greatly increased by the increase of temperature.

I. CONCLUSIONS

The following conclusions seem to be warranted from the preceding investigations.

1. Alternating-current electrolysis is not a phenomenon like direct-current electrolysis, on which definite quantitative general laws can be formulated; but is of the character of a secondary effect; that is, the action of the positive half wave is not quite reversed by the action of the negative half wave, leaving a small difference, rarely exceeding one-half percent of the electrolytic action of an equal direct current.

TABLE XVIII.

OCT. 20 TO 29, 1906. LEAD PLATES.

25 cycles, 0.1 ampere. 6.25 sq. in. total plate surface.
Duration of test, 208 hours.
Water bath heated electrically, mean temperature 39.5° cent.
Liquid, city water.

Electrolyte	Milligrammes dissolved per hour			% direct-current electrolysis	
	Chemical	Total	Electrical	Total	Electrical
a	*e*	*f*	*g*	*h*	*i*
Mixed soil	0.296	4.11	3.81	1.065	0.987
Mixed soil + 5% fertilizer	0.393	4.53	4.14	1.175	1.075

Under the conditions of the investigation, which were chosen to represent as nearly as possible actual service conditions of lead cables, alternating-current electrolysis varies from practically nothing to somewhat less than 1% of direct-current electrolysis. Since electrolytic action of the alternating current appears as a small difference between two large and nearly equal quantities, the action of the positive and of the negative

TABLE XIX.

Electrolyte	Temperature degrees centigrade	Corrosion % direct-current electrolysis			Corrosion, ratio		
		chemical	total	electrical	chemical	total	electrical
Mixed soil	22.3°	0.117	0.312	0.280	1	1	1
	39.5°	0.296	1.065	0.987	2.53	3.41	3.52
Mixed soil + 5% fertilizer	19.5	0.301	0.642	0.565	1	1	1
	39.5	0.393	1.175	1.075	1.30	1.83	1.90

half wave, a very small variation in the action of either half wave makes a very large difference in the result, and this probably accounts for the very large variation in the electrolytic action of alternating current compared with the constancy of the electrolytic action of direct current.

2. Alternating-current electrolysis, when expressed quantitatively, or in per cent, of the action of an equal direct current, varies very greatly with the chemical character of the electrolyte. The nitrates and similar compounds, as fertilizers, tend to increase electrolytic corrosion; carbonates and, in general, alkaline reaction of the soil, decreases the corrosion; that is, exert a protective action.

This protective action against alternating-current electrolysis is decreased by the presence of nitrates, etc., and is hardly sufficient to be of practical use for protecting lead cables against attack by alternating current.

3. In general, lead is more attacked than iron, and the latter shows still more erratic behavior than lead, probably due to the existence of a passive state.

4. Alternating-current electrolysis under conditions representing as nearly as seems feasible the conditions of lead cables in the soil, does not appreciably depend upon the current-density, but is practically independent thereof, except indirectly, in that very high current densities may by an increase of temperature give an increased corrosion.

5. In general, electrolytic corrosion by alternating currents increases with decrease of frequency. This increase with decreasing frequency does not follow a general law, but depends largely upon the chemical character of the electrolyte. It may be enormous; that is, 25-cycle current gives many times greater corrosion than the same current at 60 cycles. Or it may be very small and negligible. In some instances, 60-cycle current seems to give a somewhat greater attack than 25-cycle current.

In general, ammonium salts and nitrates seem to give a very great increase of electrolytic corrosion with decreasing frequency, while carbonates and soils with alkaline reaction, as containing cement, may give little or no increase of corrosion with decreasing frequency.

6. Chemical corrosion by the soil, and electrolytic corrosion by alternating current increases very greatly with increasing temperature of the soil.

J. Electrical Protection

Since the attempt to find a method of protecting lead chemically against alternating-current corrosion by mixing compounds as chalk, etc. with the soil surrounding the lead cable did not seem very hopeful, an investigation was made on the possibility of electrical protection against alternating-current electrolysis. With the tests recorded in Table XIV, a test was made on three tumblers, with ordinary mixed soil—one on 25 cycles, one on 60 cycles, and one without current, to check regarding spontaneous or chemical corrosion. In these tests a piece of sheet zinc, of about half the size of the lead plates was connected electrically with one of the lead plates. The idea was that a local action between lead and zinc would produce a direct current between lead and zinc, with the lead as negative, and thus exert a protective action.

The results of this test were:

TABLE XX

Sept. 19 to Oct. 3, 1906.

Total time of immersion of plates, 234 hours.
Duration of test with 60 cycles, 234 hours, 0.1 ampere.
Duration of test with 25 cycles, 217 hours, 0.1 ampere.
Temperature of water bath, 19.5^0 centigrade average.
Size of lead plates, 1¼ in. by 2½ in., or 6.25 sq. in. total exposed surface.
Size of zinc plates, about ½ in. by 3 in.
Electrolyte, mixed soil, city water.

No. of tumbler	No. of plate	Material	Frequency cycles	Duration of test hours	Weight of plate before test	Weight of plate after test	Difference total mg.	Electrical cor. mg.	Dissolved per hour elec. mg.	% Direct-current electrolysis
					in grammes					
7	13	lead	25	217	5.565	4.960	605	523	2.41	0.62
	14	lead			5.883	5.792	91	9	0.0415	0.0107
	14^1	zinc			5.885	5.685	200			
8	15	lead	0	234	5.095	4.992	103 }	avg.		
	16	lead			5.892	5.831	61 }	82	(.351)	
	16^1	zinc			5.734	5.067	67			
9	17	lead	60	234	5.046	4.709	337	255	1.09	0.282
	18	lead			5.900	5.817	83	1	0.0043	0.0011
	18^1	zinc			5.769	5.649	120			

While with a zinc plate connected to the lead plate a decrease of the attack should be expected—since the alternating current divides between the zinc plate and the lead plate, and the lead plate receives only a part of the total current—still the difference between the electrical corrosion of the lead plate protected by contact with the zinc plate, and the unprotected lead plate, is startling.

At 25 cycles the unprotected lead plate gives 0.623%, at 60 cycles 0.28%, of the electrolytic attack of a corresponding direct current, while the lead plate in contact with the zinc plate is practically completely protected; that is, is attacked practically no more than it would without any current, by the chemical action of the soil.

To investigate this action still further, a series of tests was made in which a small direct current was superimposed upon the alternating current. A transformer was interposed between the inverted converter which gives the 25-cycle alternating current, and the electrolytic cells, to separate the alternating-current circuit electrically from the direct-current circuit, and a small direct current sent through the cells in a divided circuit.

The 25-cycle alternating current consisted of 0.1 ampere; 0.005 ampere direct current was used, divided so that some of the cells received 1.14 milliamperes, while the others received 3.86 milliamperes, and the undivided direct current of 5 milliamperes passed through some cells without alternating-current. Resistances were inserted in both the alternating-current and the direct-current circuit, and a very high reactance of about $x = 50{,}000$ ohms, in the direct-current circuit.

The same kind of mixed soil as in the former tests was used as an electrolyte and also this soil mixed with 5% Portland cement, and this soil mixed with 5% fertilizer. City water was used as liquid. In some tests, half-size and quarter-size plates were used to get the effect of current-density. Results of the test are given in Table XXI.

The results of tests in Table XXI are extremely interesting. As seen, in many of these tests the electrical corrosion is negative: the total corrosion is less than the chemical corrosion; or in other words, if upon the alternating current a very small direct current is superimposed the total corrosion of the lead is reduced below the value which would exist with no current at all flowing.

With a direct current equal to 3.86% of the alternating current added thereto, the protection is complete; that is, in every case the lead is attacked less, sometimes less than half as much as it would be attacked spontaneously by the chemical action of the soil. Even with a direct current of only 1.14%, or about 1/90 of the value of the alternating current, the protection is

TABLE XXI.

Oct. 9 to 14, 1906. Lead Plates

25-cycle alternating current, and direct current. Duration of test, 111 hours.
Time of immersion, 114 hours. Mean temperature of water bath, 18.2° cent.

No. of tumbler	Electrolyte	Size of plate	Amperes		Mg. lead dissolved		Mg. dissolved per hour		% direct-current electrolysis		Ratio of total corrosion to chemical corrosion
			A.C.	D.C.	total	elec.	total	elec.	total	elec.	
1	Soil..............	¼	0.1	0.00114	481 48	449 16	4.28 0.428	4.08 0.144	1.11 0.111	1.035 0.0373	1.530
2	Soil..............	½	0.1	0.00114	565 67	519.5 21.5	5.08 0.594	4.68 0.194	1.32 0.154	1.215 0.0503	1.485
3	Soil..............	1	0.1	0.00114	583 88	512 17	5.23 0.776	4.61 0.153	1.355 0.201	1.195 0.0397	1.245
4	Soil and cement....	1	0.1	0.00114	621 90	503.5 —27.5	5.57 0.785	4.54 —0.248	1.445 0.204	1.175 —0.0643	0.760
5	Soil and fertilizer...	1	0.1	0.00114	605 69	534 —2.	5.43 0.605	4.81 —0.018	1.41 0.157	1.245 —0.0047	0.973
6	Soil..............	¼	0.	0.	33 31		0.280				
7	Soil..............	½	0.	0.	41 50		0.400				
8	Soil..............	1	0.	0.	71 71		0.623				
9	Soil and cement....	1	0.	0.	138 97		1.033				
10	Soil and fertilizer...	1	0.	0.	71 71		0.623				
11	Soil..............	1	0.1	0.00386	1844 65	1773 —6	16.6 0.569	16.0 —0.054	4.30 0.147	4.15 —0.014	0.915
12	Soil and cement....	1	0.1	0.00386	1759 50	1641.5 —67.5	15.8 0.425	14.8 —0.608	4.10 0.110	3.83 —0.158	0.411
13	Soil and fertilizer...	1	0.1	0.00386	1911 29	1840. —42	17.2 0.245	16.6 —0.378	4.46 0.064	4.30 —0.098	0.393
14	Soil..............	1	0.	0.005	2366 87	2295 16	21.3 0.767	20.7 0.144	110.5	107.5	1.235
15	Soil and cement....	1	0.	0.005	2356 93	2238.5 —24.5	21.2 0.812	20.2 —0.221	110.0	104.5	0.788
16	Soil and fertilizer...	1	0.	0.005	2580 49	2509. —22.	23.2 0.425	22.6 —0.198	120.0	117.0	0.583

practically complete, and the additional corrosion due to the alternating current is small compared with the chemical attack, or even negative; that is, the total attack is decreased.

This protection by a small direct current is especially effective under these conditions of the soil, where the electrolytic or chemical attack is especially great. With fertilizers, or with cement in the soil, a direct current of 1/90 the value of the alternating current reduces the corrosion below the value which it would have without any electrolytic action.

Comparing the results of Table XVII with those of XXI, it follows for mixed soil and a 25-cycle alternating current of 0.1 ampere:

Electrolytic corrosion by 25-cycle alternating current Table XVII, 0.280% of direct-current electrolysis.

Electrolytic corrosion by 25-cycle alternating current with the addition of 1.14% direct current, reduced to 0.042% of direct-current electrolysis.

Electrolytic corrosion by 25-cycle alternating current with the addition of 3.86% direct current, reduced to – 0.014% of direct-current electrolysis.

It must be noted, however, that the spontaneous or chemical corrosion in the test Table XXI, was, with mixed soil, considerably higher than the average of the previous tests.

Regarding the effect of current-density, Table XXI again shows this to be absent. The electrolytic corrosion for current-densities varying from 1 to 4; that is, with full, half- and quarter-size plates and the same current of 0.1 ampere, is of the same order.

Quarter-size plates, with a current-density of 0.1 ampere per 1.6 sq. in. or 9 amperes per sq. ft., give 0.0373% of direct-current electrolysis.

Half-size plates, with a current density of 0.1 ampere per 3.2 sq. in., or 4.5 amperes per sq. ft., give 0.0503 % of direct-current electrolysis.

Full-size plates, with a current density of 0.1 ampere per 6.25 sq. in. or 2.3 amperes per sq. ft. give 0.0397% of direct-current electrolysis.

These values do not point to a definite variation of the attack with the current-density.

The last three tests, 14 to 16, were made with direct current only, and show an electrolytic attack which is greater than the theoretical calculated from Faraday's law; that is, the corrosion of lead by direct current is greater than the theoretical value, and the direct current does not only dissolve the theoretical amount of lead, according to Faraday's law, but also increases the spontaneous corrosion due to the chemical action of the soil, especially in the presence of nitrates, etc.

Regarding the protective action of a small direct current, against alternating-current electrolysis, it must be understood that this is not due to maintaining the lead negative against the ground. It is obvious that the lead would be protected against corrosion, if upon the alternating current a direct current were superimposed sufficiently large to maintain the lead always negative. This, however, would require a direct current more than $\sqrt{2}$ times the alternating current, which is not practical. From the previous tests, it appears that a direct current of 1.5% of the alternating current gives practically complete protection against the electrolytic action of the alternating current. Such a small direct current would not appreciably change the duration of the successive half waves of alternating current, but the lead would still be positive for practically half the time; and with such a current graphically superimposed upon the alternating current, the eye would hardly see the difference in size of the two half waves of the resultant current.

It seems that a very small increase of the negative half wave over the positive half wave of the current is sufficient to make the negative half wave completely reverse and thus neutralize the action of the preceding positive half wave.

To investigate this phenomenon further in an experiment of larger magnitude, the following test was made. A lead plate was used, of 10¾-in. width, and 13¾-in. height, giving a total surface of about 2 sq. ft. It was immersed between two sheet-iron plates, as other terminal, of 5 in. by 14 in. each, in a large earthenware vessel. The lead plate was cut in two vertically, and the two halves spread apart, and in the space three small lead plates, of about 6 sq. in. each, inserted in the soil without any electrical connection, to serve as check for the chemical corrosion, due to the soil.

As an electrolyte, I used garden soil, a clay loam, with some sand, a considerable amount of street mud, and some fertilizer added. Four-ampere, 25-cycle alternating current was used and superimposed thereon, 0.06 ampere or 1.5% direct current.

The current was kept on the circuit for 20 days, from Oct. 20th to Nov. 9th, 1906, during which time the alternating current varied between 3.8 and 4.0 amperes, while the direct current remained constant at 0.06 ampere.

During the test the temperature of the soil was about 10° higher than that of the air and averaged 27.0° cent. Masses of marsh gas, with a considerable quantity of sulphuretted hydrogen, were evolved; that is, decay of organic matter took place in the soil. Evaporated water was replaced.

After the test, the lead plates were found covered with a black deposit, to which the sand stuck so that it could not be washed off, even with boiling water. With very diluted HCl, this black deposit was dissolved with the evaporation of large quantities of H_2S, and the acid was colored greenish black, as if iron had been carried across by the current and deposited as sulphide.

The test gave the following results:

Size of lead plates, both sides:	294	sq. in.
Total weight, before test	208.756	grammes
" " after "	206.975	"
Weight dissolved	1.781	"
Duration of test	470	hours
Average 25 cycles current	3.9	amperes

A. Ampere-hours, alternating current	1833
" " direct current	28.2
Dissolved per ampere-hour alternating current	.972 mg.
Theoretical attack per ampere-hour direct current	3860 mg.
Total corrosion, per cent. of direct-current electrolysis	0.0252%

B. Weight dissolved per hour and sq. in.	0.0129 mg.		
Check plates, number	1	2	3
Location	top	middle	bottom
Surface, sq. in. both sides	6.24	6.72	6.72
Weight before test	4.575	4.797	4.763
" after "	4.527	4.759	4.722
" dissolved	48	38	41
" " per sq. in. and hour	0.0160	0.0118	.0127
Average	−0.0134 mg.		
Leaves as electrical corrosion, per sq. in. and hour	−0.0005 mg.		
Amperes per sq. in., 25 cycles	0.0132		
Electrical corrosion, per cent. direct current electrolysis	−0.001%		

It seems to follow herefrom that a direct current superimposed on the alternating current and equal to 1.5% of the alternating current, perfectly protects the lead plates against electrolytic attack by 25-cycle current; so that the corrosion of the lead plates in the soil is reduced to the value of corrosion which would take place spontaneously by the chemical action of the soil, or even less.

From Table XIX it follows that the average electrolytic corrosion in ordinary soil, by 25-cycle alternating current, is 0.280% (in soil containing fertilizer, as in the last test, it is greater). 1833 ampere-hours would therefore dissolve electrically

$$1833 \times 0.0028 \times 3.86 = 19.85 \text{ grammes of lead.}$$

With a chemical corrosion of 0.0134 mg. per square inch an hour, observed, 294 sq. in. would lose in 478 hours,

$$0.0134 \times 294 \times 470 = 1850 \text{ mg} = 1.85 \text{ grammes.}$$

Without protective action by superimposed direct current, the total corrosion of the lead plates during the 20 days' test therefore should be 21.70 grammes.

By the superposition of 28.2 ampere- hours direct current, or 1.5% of the alternating current, this was reduced to 1.78 grammes, or to 8.2% of its former value, showing strong protective action of the superimposed direct current.

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A paper presented at the 214th Meeting of the American Institute of Electrical Engineers, New York, March 1, 1907.

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ELECTROLYTIC CORROSION OF IRON AND STEEL IN CONCRETE

BY A. A. KNUDSON

In these days of wide and rapidly growing use of reinforced concrete and hydraulic cements in all kinds of structures, the question often comes up as to whether concrete will afford to iron and steel the same protection from stray currents of electricity that it does from ordinary corrosion or rust. In the practice of investigating movements and results of currents upon underground pipes and other structures, several instances have come to our notice where damage has been caused by electrolytic action upon metals covered or incased in concrete or Portland cement.

During the last year we have frequently been asked about the probability of electrolysis upon various underground structures where the use of cement or concrete was being considered or had been used. In view of the importance of this question, therefore, we have thought it would be of service to those who are interested in the subject if more light were thrown on the true value of concrete as a supposed insulator. With a desire to obtain some definite data as to the amount of current and time necessary to cause corrosion upon metals encased in concrete or hydraulic cements, and also to test their value as electrolytes, we have made some laboratory experiments, and herewith give the results, trusting they may be of some value.

In March, 1903, blocks of concrete containing iron tubes were prepared by the writer for this purpose. These blocks or samples were made of equal parts of portland cement and sand. They were made in ordinary metal pails slightly larger at the top than at the bottom. In the centre of each block was placed a 2-in. wrought-iron pipe. The dimensions of each block and the surface of iron buried are given in plan and sectional drawing, Fig. 1, and will not require further explanation; the following cuts show blocks and pipes after the tests. A few preliminary tests at this time indicated that a series of tests might bear important results, and as we lacked opportunity for making daily tests and observations, they were sent to the Electrical Testing Laboratories of this city, where excellent facilities were had for making the required measurements. Preliminary tests were made with the object of "feeling our way," and of selecting such strength of current for the series as seemed advisable. These preliminary tests not being especially important, the details are not given; but from the information obtained it was decided to commence a series of tests extending over a time of 30 days with the three blocks immersed, and under the following conditions:

Block 2, Fig. 2, was immersed in fresh water and Block 4 in sea water. These were connected in series, with 0.1 ampere continuously flowing through them. Block 3, Fig. 3, was also immersed in sea water, but no current was sent through it. This was for the purpose of comparison after the blocks were broken open. The arrangement of the circuit is shown in Fig. 4.

These tests were commenced on February 1, 1906, and ended March 2, 1906. The results of importance upon this first group of blocks were found in the gradual disruption of the concrete, as shown by the cracks as time went on, and the appearance of electrolysis and loss in weight of the iron tubes of both No. 2 and No. 4 when the tests were concluded. Block 4 is not shown, it being quite similar to the others. During the test these cracks were noted as follows: on the 17th day a small crack down one side of Block 2 was observed. On the 27th day this crack in No. 2 had a maximum width of $\frac{1}{8}$ in. and extended clear down one side, across the bottom, and nearly to the top of the other side. Two cracks also appeared in No. 4. This disintegration of the concrete was a genuine surprise. The report furnished by the laboratory on this first set of experiments concludes as follows:

> After the conclusion of this test which extended over thirty days time, the blocks were removed, and after allowing them to dry they were broken open. It was found to be quite easy to break open blocks Nos. 2 and 4 which had already become cracked. Block No. 3 which had not been subjected to electrolysis was broken with the greatest difficulty. Blocks Nos. 2 and 4 showed on their interior strong evidences of electrolytic

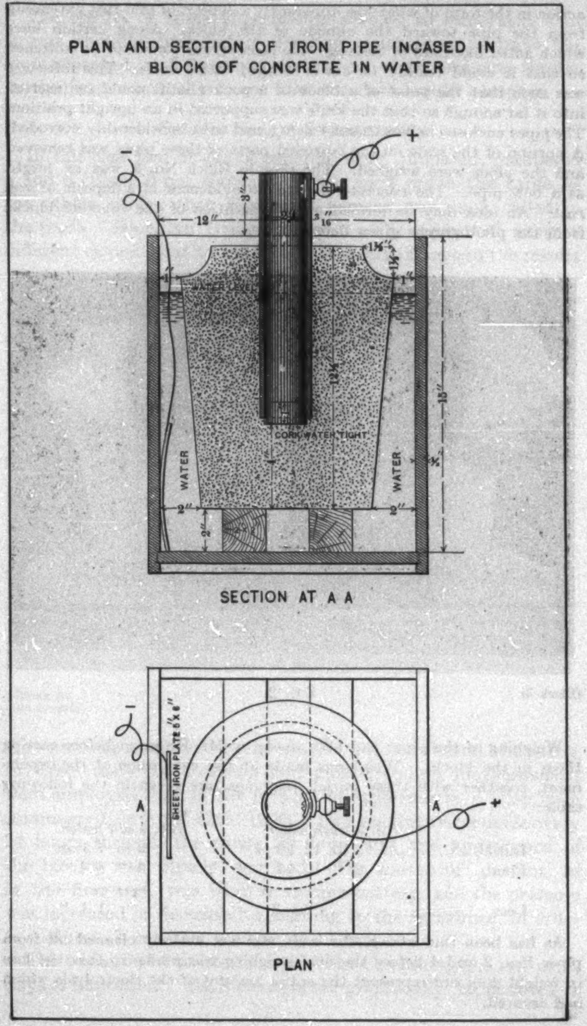

PLAN AND SECTION OF IRON PIPE INCASED IN BLOCK OF CONCRETE IN WATER
+
−
3"
12"
2¼
3/16"
1½"
1½"
1"
1"
WATER LEVEL
12¾
15"
CORK WATER TIGHT
WATER
WATER
½"
2"
2"
2"
SECTION AT A A
−
SHEET IRON PLATE ¼" 5 X 6"
A
A
+
PLAN

Fig. 1.

action in the form of what was apparently a deposit of iron rust extending from the pipe toward the outside of the block. Along certain lines which acted like lines of cleavage, the cement was found to be softened so that it could readily be cut or scraped with a knife. This softening was such that the point of a blade of a pocket knife could be inserted into it far enough so that the knife was supported in an upright position. The pipes enclosed in Nos. 2 and 4 were found to be considerably corroded. A portion of the scale on the corroded parts of these pipes was removed and the pipes were weighed. The pipe in Block No. 3 was as bright as a new pipe. The concrete showed no evidences of a deposit of iron rust. An idea may be formed of the condition of the concrete blocks from the photographs given herewith.

(Block 2) FIG. 2.

Weighing of the pipes had been made by Mr. Knudson before casting them in the blocks. Weighings made at the conclusion of the experiment, together with these initial weighings, are given in the following table:

	No. 2 fresh water.	*No. 4. salt water.*
Initial	3 lb. 12.50 oz.	3 lb. 7.5 oz.
Final	3 " 10.95 "	3 " 6.4 "
Loss	1.55 "	1.1 "

As has been said above, the scale was not entirely cleaned off from pipes Nos. 2 and 4 before the final weighing was made, so that the loss in weight does not represent the entire amount of the electrolysis which had occured.

The results of these experiments seemed so important that it was thought best before drawing conclusions to have the tests repeated, and therefore another set of experiments similar to the first, was made to see how the data would compare.

SECOND SET OF EXPERIMENTS

In this case two blocks of concrete were prepared, numbered 5 and 6 (Block 6 not shown). These were made the same as the others except that Rosendale cement was used, called in the trade "Brooklyn Bridge Brand." The object of using a different cement was to see if there was any change in the results that could be attributed to the use of a different brand of cement. In these tests more careful and more frequent measurements were employed than in the first set of experiments. They were commenced on April 12th, 1906. Two readings were made every 24 hours through the entire 30 days, and the appearance of the blocks was closely watched. The source of current, as in the first test, was from a storage-battery, and the pressure was increased or decreased according to the resistance, in order to maintain a constant current of 0.1 ampere.

(Block 3)
(no current)

FIG. 3.

The variation of resistance in both blocks during the test of 30 days is important. Such changes are graphically represented in

Fig. 6. The figures showing ohms are given as relative, as they may not quite accurately represent the true values. They were obtained by simply dividing the volts by the 0.1 ampere. It was found in the preliminary trials that resistance measurements by the usual methods, such as the Wheatstone bridge, were not accurate, owing to strong polarizing effects. For this reason the resistances as shown by these curves while not considered absolutely accurate in every case, are sufficiently so for our purpose of examination and study.

The curve in Fig. 7 represents the sudden fall or practical breakdown of concrete as insulation in 48 hours. The measurements in this test were made by the Wheatstone bridge, using alternating current and a telephone receiver. They are considered fairly accurate.

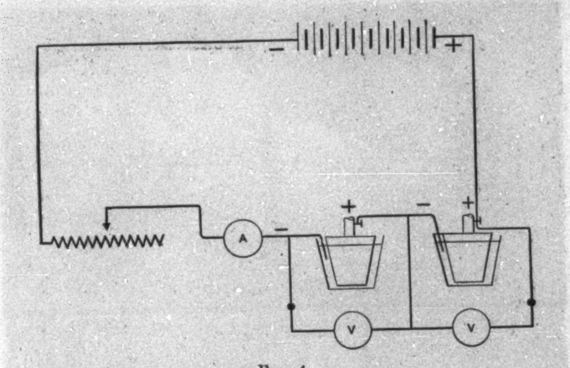


Fig. 4.

Quoting from the report on this second series of tests, the following notes are of interest:

Second day of test. Water appeared around the pipe of No. 5, having soaked through the concrete.

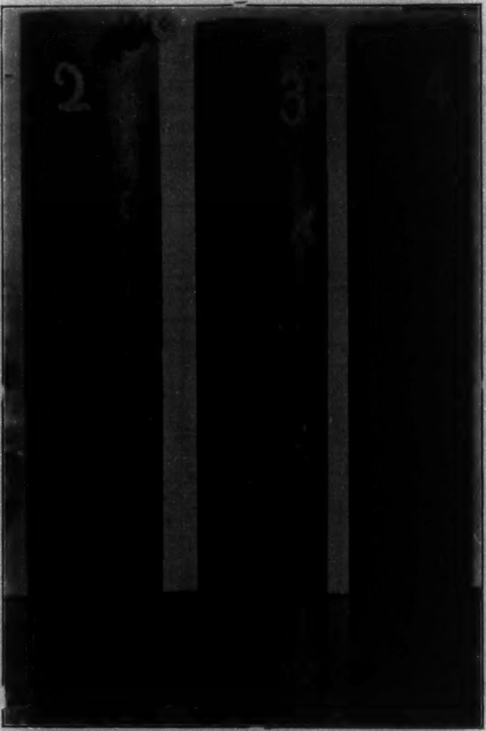
Sixth day of test. Cracks were observed in both samples of concrete, those in No. 5 being the most prominent. A small amount of water was found standing in the bottom of pipe No. 5. None in pipe No. 6.

Seventh day of test. The cracks in the concrete are increasing in the case of both samples.

Ninth day of test. A yellow frothy substance appeared at several points at the top of the concrete, close to the iron pipe of sample No. 6. Later this turned rust color.

Eleventh day of test. Same rust colored deposit observed around pipe of sample No. 5. The cracks of both samples have increased in prominence.

Eighteenth day of test. The cracks have assumed such proportions that it appears as though the concrete might easily fall apart, being $\frac{1}{8}$ to $\frac{3}{16}$ of an inch in many places. There is considerable rust colored, frothy deposit on top of sample No. 5, especially near the pipe.



(GROUP 1)
(1st series)

FIG. 5

It appears from these observations that before the ninth day, the process of electrolysis had arrived at quite an advanced stage on both blocks and before the rise in resistance took place, which afterwards in fresh water reached 300 to 400 ohms, requiring some 30 to 40 volts to maintain the 0.1 ampere. We should not, therefore, conclude that because such high readings are not found in practice, it is a sign that there can be no electrolysis. In the salt-water block it is observed that even to the eleventh day of the test 5.5 volts only were required to pass the 0.1 ampere, and

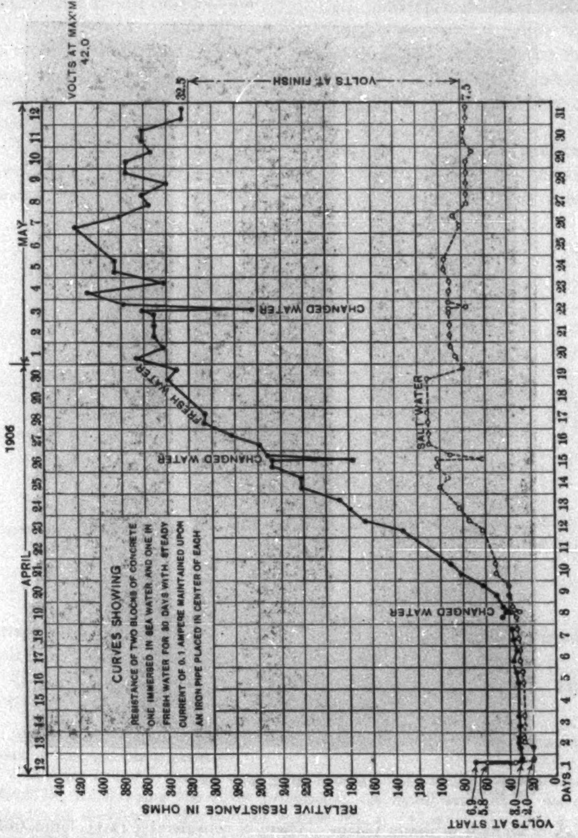


FIG. 6.

at that time the record states the cracks in both samples have increased in prominence.

This report concludes as follows:

> After the conclusion of the test which continued over thirty days time, the concrete blocks were removed from the water and allowed to dry. They were then broken open. Block No. 5 which had been under test in the salt water was found to have a rust colored deposit extending along the sides of a crack from the external surface to the pipe, as shown by the accompanying photograph. The rust colored deposit in sample No. 6 was only about the pipe.
>
> There were spots especially in the fresh water block No. 6 where the concrete had softened to such an extent as to be readily dug out with a knife.

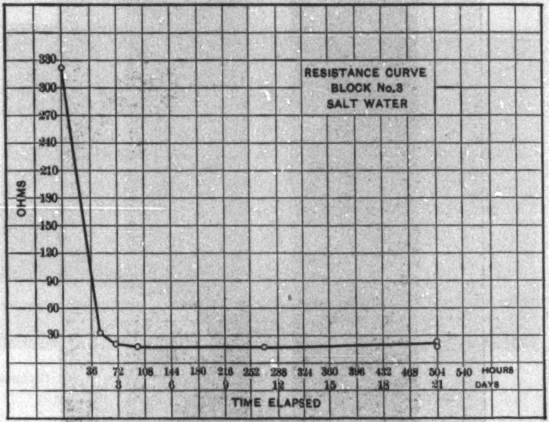


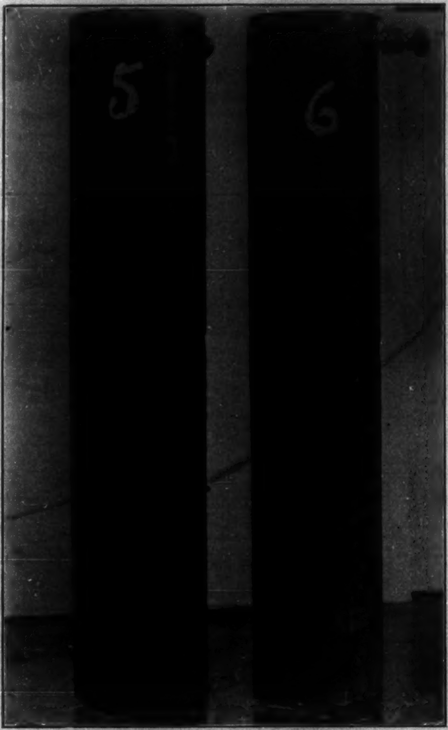
FIG. 7.

The weights of the pipe before and after the tests are given in the following table:

	No. 5 salt water.	*No. 6 fresh water.*
Initial	3 lb. 7.1 oz.	3 lb. 6.6 oz.
Final	3 5.5 "	3 5.5 "
Loss	1.6 oz.	1.1 oz.

Since the scale was not entirely removed for the final weighing, the loss in weight indicated does not represent the actual total amount of electrolysis which had occurred. However, all scale that could be readily removed was removed by Mr. Knudson before the final weights were taken.

This second series of tests shows results very similar to the first, only more pronounced; and we believe it also shows that the results would be practically the same with concrete made up with any of the different brands of cement found in the market, or made with different proportions of sand, or made of brick, or stone masonry.



(GROUP 2)
(2d series)
FIG. 8.

The photographs of the different pipes show to some extent the effects of electrolytic action upon their surfaces which were in the concrete, except No. 3, Fig. 5, which had no current. No. 5, Fig. 8, which was in the salt-water block, shows the most severe case, having a hole through the iron. This hole is one inch long and three eighths of an inch wide at its widest part, as genuine a case of electrolysis as any we have seen in larger pipes removed from a street.

Referring to the photographs of the blocks, all but No. 3 (which had no current) show the discoloration made by the iron rust, extending in most cases through what were cracks to the outside surface. No. 3 shows a perfectly clean and hard interior surface. As the report states, there was no evidence of corrosion. It was like breaking open a piece of granite, and required the services of a " hard-handed son of toil " with a sledge-hammer and chisel. The other blocks which were under test could be pried apart with an ordinary screw-driver inserted in the cracks.

(Block 5) FIG. 9.

Attention is called to block 5. Fig. 9 (sea water) where one of the cracks is shown at the back and about the centre of the curve from which the iron tube was removed. The object of using sea water in our tests, as well as fresh water, was to ascertain and compare the resistances shown in the curve sheet, and also to conform as nearly as possible to conditions found in practice, such as bridge-piers and other structures located on water-fronts.

These tests and experiments go to show that only a small fraction of an ampere is necessary to cause electrolytic action. The element of time being always with us, it is only necessary where electric currents are present of sufficient voltage in the proper direction to cause even a very small amount of current to pass that will in time cause corrosion upon interior steel structures, whether placed in concrete, brick, or in granite masonry. It is not expected, however, that large granite piers would develop cracks, but electrolysis to interior steel work and to bridge anchorages may go on just the same. Cracks may develop, however, in concrete piers of small bridges, such as those which cross creeks or canals.

By way of a practical illustration, there is a bridge in this city of this description over the Gowanus canal, South Brooklyn, at Hamilton avenue. A portion of the Bridge Commissioner's report ending June 30, 1906, referring to this bridge, is as follows:

> HAMILTON AVENUE BRIDGE.
>
> Since construction, the foundation walls of this bridge have developed some rather serious cracks, occurring on both sides of the canal, and there has been a movement of the walls towards the centre of the canal. During the last three months this movement has amounted to half an inch. Previously the movement totaled about three and one-half inches. From October to March there was practically no movement. A continuation of this movement for several inches more will result in the necessity of alterations in the centre of the leaves, as they will interfere before the bridge can be fully closed.

With a view of ascertaining the electrical conditions, we have made a few tests at this bridge. The voltmeter readings show the steel structure to be positive to the canal, positive to water-mains in the street, and positive to the trolley-rails on the bridge, ranging from 0.5 to 1.5 volts. These readings were taken when the car-traffic was light. Some of the cracks on the concrete had been plastered over, but others were quite visible. The tests indicate that the trolley tracks on the bridge are in connection with the steel structure. Tests were also made on another bridge of the same construction a little farther north over the same canal, at Ninth street. The readings here were exactly the reverse of those found at the Hamilton avenue bridge, the structure being negative to canal, to water-mains and tracks. There were no visible cracks in the concrete of either foundation. Although the cracks in the concrete of the Hamilton avenue bridge are attributed to other causes in the Commissioner's report, we believe these tests and observations point strongly to electrolytic action from trolley currents as being the true cause. This seems to us the more reasonable cause for these cracks, in view of the results of our laboratory experiments just described. Ordinary care would suggest that costly structures of this kind in this or other cities should be periodically inspected for evidence of electrolytic action upon the interior steel work, especially if located contiguous to water, or in the vicinity of electric railways or railway power stations as in the case just cited. Furthermore, this question should be carefully considered when such structures are planned, and tests made at locations of proposed bridges or other structures to ascertain the electrical conditions and the possibilities of injury due to electrolysis from stray currents.

This question of electrolytic corrosion of interior steel in the construction of high buildings, however, has not been entirely neglected. There is at least one case, that of the *New York Times* building, where provision has been made in advance as a protection. In the Building Supplement, issued by that paper, dated January 1st, 1905, an interesting description is given in detail of the entire construction of that building. The following extract, referring to electrolysis, will be of interest:

> The danger that in the case of the steel frame, rust and the disintegration of electrolysis would hasten the process of dissolution so much as to make structures of this kind prematurely unsafe through the destruction of their supports, was recognized in time to permit of ample safeguarding in the case of the steel frame of the Times building. It is axiomatic that columns to which moisture has no access will not be impaired by rusting, and that those effectually insulated from vagrant electrical currents will not be affected by electrolysis. The first consideration was to keep the basements dry. Hence the thorough waterproofing and draining of the retaining walls already described, which was carried under the floor of the press room, occupying the great area of the sub-basement. As a further safeguard, all the steel members up to the street level are incased in Portland cement mortar, to the minimum thickness of three-fourths of an inch. This is effectual protection against rust deterioration. Under these conditions electrolytic disintegration is deemed impossible, but the probability of its occurrence in even microscopic degree is rendered still further remote by as perfect insulation as can be provided. There is sufficient grounding to relieve any electrical tension which may exist in any part of the steel frame by drawing off the current at points where electrolytic action cannot be set up.

This is the first instance we have noticed where a large corporation has recognized this danger and has taken steps beforehand to avoid it. The protection of steel structures already constructed, however, is a different matter. While plans may be made to provide insulating methods and waterproofings, before construction, it is not easy to prevent corrosive action, when the conditions are favorable, after construction.

Another point which may have an important bearing on this subject is the great pressure upon pillow-blocks, and upon piers supporting as they do enormous weights, which serve to make excellent electrical contact with concrete or masonry on which they stand, and, therefore, offer further opportunity for inviting stray currents.

Figs. 10 and 11 are photographs of the underside of two water meters which were practically destroyed by electrolysis while in service in the cellars of dwellings in a distant city. They were discovered during a survey by the writer in October last. They are shown as an illustration of how railway currents will follow a service pipe for a considerable distance from the tracks, enter a building, and find an outlet to ground in the damp soil of a cellar. This furnishes an opportunity for current to pass into the iron foundations of large buildings where such service pipes, either water or gas, are connected, as they usually are, to the framework of such structures.

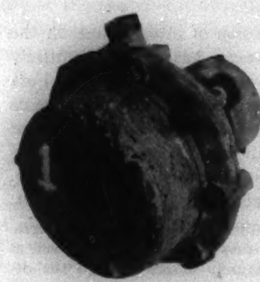


FIG. 10.—300 ft. from nearest track.

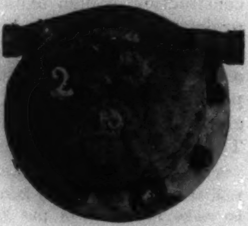


FIG. 11.—675 ft. from nearest track

These illustrations are by no means isolated cases. We have discovered many similar cases of current straying into buildings in different cities in this country. There were three meters found destroyed in this way in different sections of the city from which they were taken. They were from one to two miles apart. The distance from the tracks of Fig. 10 was

300 ft., and of Fig. 11, 675 ft. All of these meters were on side streets, at right angles to the car tracks.

IN REGARD TO REMEDIES

Coatings of various kinds of paints or varnishes will be of little use as an insulation, for it must be borne in mind that not only a moisture resistant is required, *but an insulation that will resist continual moisture*, and also that will stand the pressure of great weights.

From these laboratory experiments, as well as observations in practice, we draw the following conclusions.

1. Steel structures are well preserved from ordinary corrosion by concrete if placed either in salt or fresh water. This, however, has long been known.
2. If but a small fraction of an ampere of electricity passes from an interior metallic column or structure into concrete or masonry as usually made, there will be corrosion of the metal and disintegration of the concrete or masonry.
3. Structures of steel in concrete that are subject to sea water are in more danger from electrolytic action than those in fresh water, by reason of the lower resistance of concrete in sea water as shown by the laboratory experiments.
4. In no sense can concrete be considered an insulator, and, as shown, it is from all appearances just as good an electrolyte as any of the soils found in the earth.

Other investigators in this field have given valuable information on this subject. Mr. Maximilian Toch, in a paper before the American Electrochemical Society in June last, gives an interesting account of some experiments conducted by himself with steel in concrete, and although on somewhat different lines to our own, arrives at practically the same results.

Mr. M. P. Wood, in his excellent work entitled "Rustless Coatings, Corrosion, and Electrolysis of Iron and Steel," refers to this subject as follows:

> It is a false reliance that masonry, mortar, concrete, or cement are impervious to moisture and incapable of acting as an electrolyte such as would induce electrolysis. They are not insulating substances, or at the best only in the smallest degree under the most favorable circumstances. They are positively porous and in nearly every case, whether tested in large or small mass, are permeable to all waters or moisture and gases, and in but a few exceptional cases ever become thoroughly dry.

It is therefore to be expected that so long as the single trolley with its grounded return is in general use, just so long may we look for electrolytic action in some form upon various underground structures; and reinforced concrete is no exception to the rule.

It is not at all surprising that such currents are busy at steel work of bridge-anchorages. Whether enclosed in concrete or masonry, these materials, as we have endeavored to show, are no protection from straying railway currents when the conditions are favorable for electrolytic action. In view, therefore, of these items presented and the enormous use to which concrete and hydraulic cements are now put, it would seem that this question should receive due consideration by those who have to do with planning and constructing important public works and buildings, as well as those who are entrusted with the care and safety of such structures.

A paper presented at the 214th Meeting of the
American Institute of Electrical Engineers
New York, March 1, 1907.

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SOME THEORETICAL NOTES ON THE REDUCTION OF EARTH CURRENTS FROM ELECTRIC RAILWAY SYSTEMS BY MEANS OF NEGATIVE FEEDERS

BY GEORGE I. RHODES

The subject of earth currents caused by electric railway systems is of such importance that it is believed a few theoretical notes on the relative efficiencies of different return feeder systems in reducing stray currents will not be without interest.

Consider any system, the potential of whose running rails may be represented by the Curve *I*, Fig. 2, which is plotted with distances from the power house or sub-station as abscissas, and potentials of the rails referred to the negative bus-bar as ordinates. Assume for the time being that all resistance offered to current flowing from the tracks to earth is in the contact between rails and earth.

Let a = contact resistance per foot between rails and earth.
l = distance from power station.
v = potential of rails referred to negative bus-bar.
I_g = total leakage current.

Now if the negative bus-bar is completely grounded, and the earth of uniform potential, as would be the case if it had zero resistance,

$$\Delta I g = \frac{v \Delta l}{a}$$

$$g = \sum \frac{v \Delta l}{a}$$

If a is uniform over the entire line, it is evident that the leakage current will be measured by the area enclosed between the potential curve of the track and the line of zero potential. If the contact resistance is not uniform, the area will not be a true measure, but it will still be indicative of the amount of current flowing from the rails.

If now the negative bus-bar is insulated, the earth will have a potential with reference to it such that the current flowing out of the rails shall be equal to that flowing into them. Under the assumption of uniform contact resistance between track and ground, this potential will be such that the areas enclosed by the curve, above and below the line of earth potential, are equal.

The assumption that the earth is of uniform potential is obviously far from correct, for since its resistance is not zero it is affected to a certain extent by the presence of a grounded conductor of different potential. If the curve is plotted with reference to the ground in the vicinity of the rails as zero, the area enclosed by the curve will then measure the true leakage current with the above limitations; but if the curve is plotted with reference to the earth at that point where the rails and ground are at the same potential, the area enclosed will not measure the actual leakage, but rather the maximum current that would flow if the earth offered no resistance except at the surface of contact with the rails.

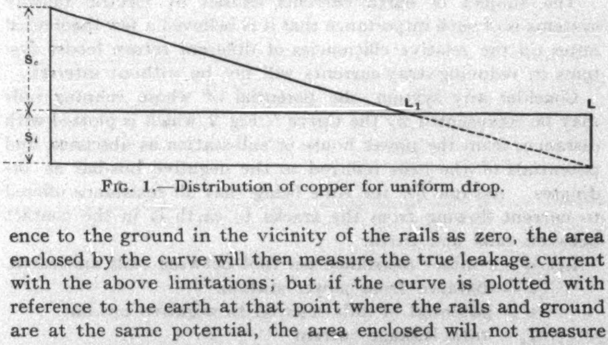


FIG. 1.—Distribution of copper for uniform drop.

On this latter assumption, then, the following cases will be considered, both with the negative bus-bar thoroughly grounded and insulated. The load is considered to be uniformly distributed over the whole line, which extends in one direction only from the power station.

I. No copper in return circuit.

II. Copper of uniform section bonded to the rails at short intervals.

III. Copper distributed to give uniform drop, bonded to the rails at short intervals.

IV. A single insulated negative feeder connected to rails at middle of the line, and at the power station.

V. A single insulated feeder connecting the rails to the negative bus-bar only at the middle of the line.

VI. Several insulated feeders.

VII. Several insulated feeders with equal potentials at all feed points.

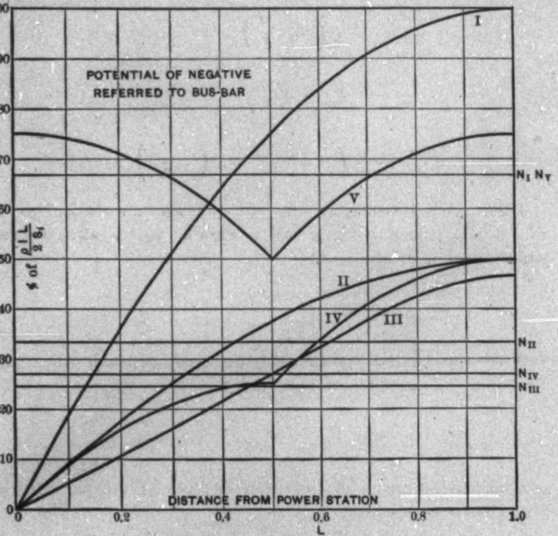


FIG. 2.—Potential Curves, Cases I–V.

The following notation will be used:

i = current at any point on line.

I = total current.

v = potential at any point referred to bus-bar as zero.

l = distance from power station.

L = total length of line.

r = resistance per foot of return.

ρ = 10.30 = resistance per cir. mil-foot of copper.

ω = 0.00,000,302 lb. = weight per cir. mil-foot of copper.

s_i = equivalent conductivity of track rails in cir. mils of copper

s_c = cir. mils of return copper at power station.

W = weight of return copper.

A = area representing leakage current with negative bus-bar grounded.

a = area representing leakage current with negative bus-bar insulated.

I. No return copper.

$$i = I\left(1 - \frac{l}{\mathrm{L}}\right)$$

$$r = \frac{\rho}{s_i}$$

$$V = \int i\, r\, d\, l = \frac{\rho\, I}{s_i}\left(l - \frac{l^2}{2L}\right)$$

The curve represented by this equation and shown as Curve I, Fig. 2, is a parabola whose axis is parallel to the axis of v and whose apex is at the point

$$l = L \quad v = \frac{\rho\, I\, L}{2\, s_i}$$

With the bus-bar grounded, the area beneath the curve measures the leakage current, and is,

$$A = \frac{\rho\, I\, L^2}{3\, s_i}$$

as obtained by means of the usual formula giving the area enclosed by a parabola.

With the bus-bar insulated, it can be shown by equating the areas enclosed by the curve above and below the neutral line that the earth and rail are at the same potential at the point

$$L_0 = L\left(1 - \frac{1}{\sqrt{3}}\right)$$

and the area representing leakage current is

$$a = \frac{1}{3\sqrt{3}} \quad \frac{\rho\, I\, L^2}{3\, s_i}$$

II. Return copper of uniform section.

$$i = I\left(1-\frac{l}{L}\right) \text{ as before}$$

$$r = \frac{\rho}{s_i+s_c}$$

$$v = \frac{\rho\, I}{s_i+s_c} \cdot \left(l-\frac{l^2}{2\,L}\right)$$

The curve representing this equation when $s_c = s_i$ is shown as Curve *II*, Fig. 2. It is a parabola as in Case I, but its ordinates bear the ratio $\frac{s_i}{s_i+s_c}$ to those of the first curve.

The area representing leakage current with grounded bus-bar can be shown to be

$$A = \frac{s_i}{s_i+s_c} \quad \frac{\rho\, I\, L^2}{3\, s_i}$$

and with the bus-bar insulated the neutral is at

$$L_0 = L\left(1 - \frac{1}{\sqrt{3}}\right)$$

making

$$a = \frac{s_i}{3\,\sqrt{3}\,(s_i+s_c)} \quad \frac{\rho\, I\, L^2}{3\, s_i}$$

The weight of copper is

$$W = \omega\, s_c\, L$$

III. Copper distributed for uniform drop.

$$i = I\left(1-\frac{l}{L}\right) \text{ as before}$$

$$r = \frac{\rho}{(s_i+s_c)\left(1-\frac{l}{L}\right)}$$

That is, the conductivity is proportional to the current.

$$v = \frac{\rho I l}{s_i + s_c} \text{ a straight line.}$$

It is evident that this equation can hold only when l is such that

$$(s_i + s_c)\left(1 - \frac{l}{L}\right) = s_i$$

then
$$l = L_1 = L\,\frac{s_c}{s_i + s_c}$$

For values of $l > L_1$, the conductivity is uniform and equal to that of the rail return (see Fig. 1).

From $l = L_1$ to $l = L$

$$i = I\left[\frac{L - L_1}{L} - \frac{l - L_1}{L}\right]$$

$$r = \frac{\rho}{s_i}$$

$$v = \frac{\rho I}{s_i}\left[\frac{(L - L_1)\ (l - L_1)}{L} - \frac{(l - L_1)^2}{2L}\right] + \frac{\rho I L_1}{s_1 + s_c}$$

This curve is that portion of the parabola I, Fig. 2, beyond $l = L_1$, dropped until it is tangent to the straight line.

$$v = \frac{\rho I l}{s_i + s_c}. \quad \text{See III, Fig. 2.}$$

The area representing leakage current with the bus-bar grounded can be shown to be

$$A = \frac{s_i\ (3\,s_c^2 + 6\,s_i\,s_c + 2\,s_i^2)}{2\,(s_i + s_c)^3} \cdot \frac{\rho I L^2}{3\,s_i}$$

and with the bus-bar insulated the neutral point is at

$$L_0 = \frac{L}{2}\left\{1 - \frac{s_i^2}{3\,(s_1 + s_c)^2}\right\}$$

for values of $s_c > 0.815\,s_i$, making $L_1 > L_0$.

This makes

$$a = \frac{s_i\ (3\,s_c^2 + 6\,s_i\,s_c + 2\,s_i^2)^2}{24\,(s_i + s_c)^5} \cdot \frac{\rho I L^3}{3\,s_i}$$

The weight of copper used is

$$W = \omega\, s_c \frac{L_1}{2} = \frac{\omega\, s_c^2\, L}{2\ (s_i+s_c)}$$

In order to compare properly this case with Case II, equal amounts of copper must be used making

$$\frac{s_{c_{\text{III}}}^2}{2\ (s_i+s_{c_{\text{III}}})} = s_{c_{\text{II}}}$$

$$s_{c_{\text{III}}} = s_{c_{\text{II}}} + \sqrt{s_{c_{\text{II}}}^2 + 2\, s_i\, s_{c_{\text{II}}}}$$

IV. Single insulated return feeder from middle of line. Connection to rails at power house.

By the use of Kirchoff's laws it can be shown that

From $l = o$ to $l = \frac{L}{2}$

$$i = I\left(1 - \frac{3\, s_c}{4\,(s_i+s_c)}\right) - I\,\frac{l}{L}$$

$$r = \frac{\rho}{s_i}$$

$$v = \frac{\rho\, I}{s_i}\left\{ l\left(1 - \frac{3\, s_c}{4\ (s_i+s_c)}\right) - \frac{l^2}{2\,L}\right\}$$

From $l = \frac{L}{2}$ to $i = L$

$$i = \frac{I}{2} \quad \frac{I\left(l - \frac{L}{2}\right)}{L}$$

$$v = \frac{\rho\, I}{s_i}\left\{ \frac{\left(l - \frac{L}{2}\right)}{2} - \frac{\left(l - \frac{L}{2}\right)^2}{2\,L} + \frac{L}{2}\left(\frac{3\, s_i}{4\,(s_i+s_c)}\right)\right\}$$

Both curves are portions of the parabola of Case I (see IV, Fig. 2)

The area representing leakage current can be shown to be

$$A = \left\{1 - \frac{27\, s_c}{32\ (s_i+s_c)}\right\} \quad \frac{\rho\, I\, L^2}{3\, s_i}$$

and with the bus-bar insulated

$$L_0 = L \left\{ 1 - \frac{1}{\sqrt{3}} \sqrt{1 - \frac{9\, s_c}{16\,(s_i + s_c)}} \right\}$$

making $$a = \frac{1}{3\sqrt{3}} \left(1 - \frac{9\, s_c}{16\,(s_i + s_c)} \right)^{\frac{3}{2}} \frac{\rho\, I\, L^2}{3\, s_i}$$

The weight of copper used is

$$W = \frac{\omega\, s_c\, L}{2}$$

Making for proper comparison with Cases II and III

$$s_{c_{\text{IV}}} = 2\, s_{c_{\text{II}}}$$

V. A single insulated return feeder from middle of iine. No other connection to rail.

It can be shown that from $l = o$ to $i = \frac{L}{2}$

$$i = -\frac{l\, I}{L}$$

$$v = \rho\, I\, L \left[\frac{1}{2\, s_c} + \frac{1}{8\, s_i} \right] - \frac{\rho\, I\, l^2}{2\, L\, s_i}$$

and from $l = \frac{L}{2}$ to $l = L$

$$i = \frac{I}{2} - \frac{I}{L}\left(l - \frac{L}{2} \right)$$

$$v = \frac{\rho I}{s_i} \left\{ \frac{\left(l - \frac{L}{2} \right)}{2} - \frac{\left(l - \frac{L}{2} \right)^2}{2\, L} + \frac{L\, s_i}{2\, s_c} \right\}$$

These are two symmetrical portions of the parabola of Case I intersecting at the point $l = \frac{L}{2}$ $v = \frac{\rho\, I\, L}{2\, s_c}$ (see V, Fig. 2).

With the bus-bar grounded the area representing leakage current is

$$A = \frac{6\,s_i + s_c}{4\,s_c} \cdot \frac{\rho\, I\, L^2}{3\,s_i}$$

and with the bus-bar insulated there are two neutral points at

$$L_0 = \frac{L}{2\sqrt{3}} \text{ and } L_0 = \frac{L}{2}\left[1 - \frac{1}{\sqrt{3}}\right]$$

making
$$a = \frac{1}{12\sqrt{3}} \cdot \frac{\rho\, I\, L^2}{3\,s_i}$$

The weight of copper is the same as in Case IV.

VI. With several insulated feeders the potential curve will take a form similar to that of Case V in which the curve between any two feeders is a portion of the parabola of Case I. If the feeders are of uniform size, the general form of the potential curve will approach the straight line of Case III as the number of feeders is increased indefinitely. With a single feeder the area measuring leakage current is larger than for the case with the copper distributed for uniform drop, and with increasing number of feeders this area will approach it as a limit.

With feeders graded in size to give uniform potential at the feed points the curves will be of the forms in Case VII.

VII. Several insulated feeders with equal potentials at feed points.

In this case the uniformly equal potentials at the ends of feeders may be secured by properly adjusting the sizes or by means of negative boosters. By adjustment of sizes, the potential of the track must necessarily be greater than that of the bus-bar, and if there is a solid ground at the power station there will be a leakage current due to this difference; but with the use of boosters the potentials at the ends of the feeders can be maintained uniform with the negative bus-bar, and furthermore, this, with a widely fluctuating load such as is the case on an electric railway.

For the best results with a given number of feeders it is evident that they must be connected to the rails at such points as will give equal maxima on the potential curves. This may be accomplished in two ways, viz.:

1. No connection to rails at power station, and distance between feed points twice the distance from the power house to the first point, and from the last point to the end of the line. (See Fig. 3.)

2. Connection to rails at power house with the distance between feed points, and from the power station to the first feed point equal to twice the distance from the last point to the end of the line. (See Fig. 4.)

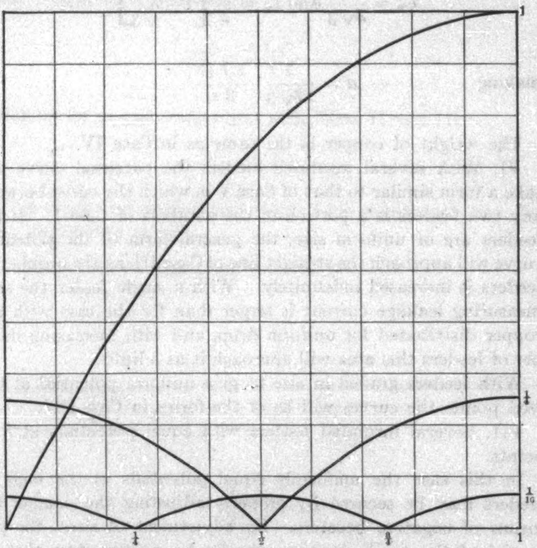


FIG. 3.—Potential of negative referred to bus-bar.—Case VII.

1. With a single feeder and no connection at power house, the feed point for equal maxima will be at the centre of the line. (See Fig. 3.) the potential curve being made up of the upper portions of the parabola of Case I, also shown in Fig. 3.

With the bus-bar grounded the area beneath this curve is

$$A = 2 \times \frac{2}{3} \times \frac{L}{2} \times \frac{1}{4}\,\frac{\rho\, I\, L}{2\, s_i} = \frac{1}{4}\,\frac{\rho\, I\, L^2}{3\, s_i}$$

With two feeders the feed points will be ¼ and ¾ of the distance from the power house and the area will be

$$A = 4 \times \tfrac{2}{3} \times \frac{L}{4} \times \tfrac{1}{16} \times \frac{\rho I L}{2\, s_i} = \tfrac{1}{16}\, \frac{\rho I L^2}{3\, s_i}$$

With *n* feeders the feed points will be at

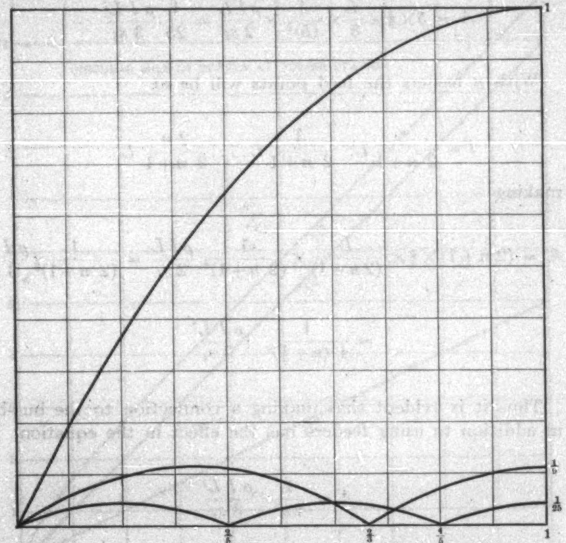


Fig. 4.—Potential of negative referred to bus-bar.—Case VII.

$$\frac{1}{2\,n},\ \frac{3}{2\,n} \cdots \frac{2\,n-1}{2\,n}$$

of the distance from the power house to the end of the line, making

$$A = 2\,n \times \tfrac{2}{3} \times \frac{L}{2\,n} \times \frac{1}{(2\,n)^2} \times \frac{\rho I L}{2\, s_i} = \frac{1}{4\,n^2}\, \frac{\rho I L^2}{3\, s_i}$$

2. With one feeder the point of connection to the rails will be at $l = \frac{2}{3} L$, making

$$A = 3 \times \tfrac{2}{3} \times \frac{L}{3} \times \frac{1}{(3)^2} \times \frac{\rho I L}{2 s_i} = \frac{1}{9} \frac{\rho I L^2}{3 s_i}$$

With two feeders the points of connection will be at $l = \frac{2}{5} L$, and $\frac{4}{5} L$, making

$$A = 5 \times \tfrac{2}{3} \times \frac{L}{5} \times \frac{1}{(5)^2} \times \frac{\rho I L}{2 s_i} = \frac{1}{25} \frac{\rho I L^2}{3 s_i}$$

With n feeders the feed points will be at

$$l = \frac{2}{2n+1} L, \quad \frac{4}{2n+1} L \ldots \frac{2n}{2n+1} L$$

making

$$A = (2n+1) \times \tfrac{2}{3} \times \frac{L}{(2n+1)} \times \frac{1}{(2n+1)^2} \frac{\rho I L}{2 s_i} = \frac{1}{(2n+1)^2} \frac{\rho I L^2}{3 s_i}$$

$$= \frac{1}{4 (n+\frac{1}{2})^2} \frac{\rho I L^2}{3 s_i}$$

Thus it is evident that making a connection to the bus-bar in addition to using feeders has the effect in the equation

$$A = \frac{1}{4 n^2} \frac{\rho I L^2}{3 s_i}$$

of increasing the number by ½ a feeder. This will explain the points as the curve in Fig. 8 of ½, 1½, 2½ feeders, etc.

If the bus-bar is insulated the equation for area representing leakage current is

$$a = \frac{1}{12 \sqrt{3}\, n^2} \frac{\rho I L^2}{3 s_i}$$

In the case of insulated feeders with negative boosters the leakage current from rails to ground is entirely independent of the amount of copper used, and the size of feeders is determined solely by the cost of copper and of power necessary to run the boosters.

Having now found equations representing the leakage currents for the different cases, let us now compare them. Fig. 5 gives the cross-section of the copper at the power station in the several cases, to give equal weights of copper, the unit of weight

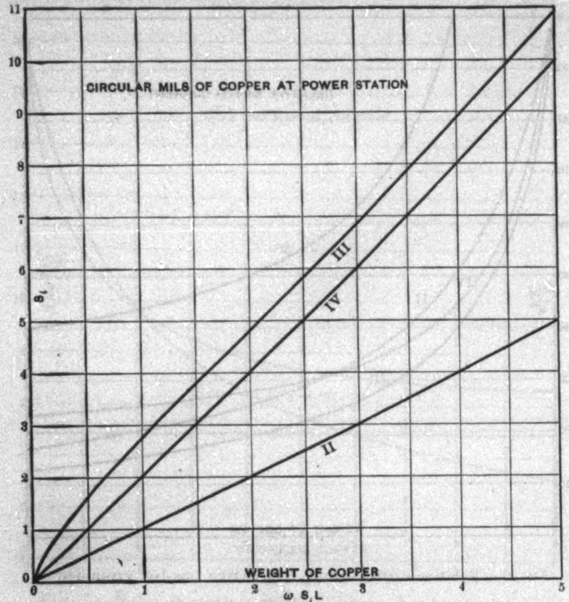


Fig. 5.

being $\omega\, s_i\, L$, or a weight of copper of length L which gives a conductivity equal to that of the rails.

Fig. 6 gives the relative leakage currents for the several cases (in which the bus-bar is grounded) plotted to amount of copper used. The unit of leakage current is taken as that which occurs on a line without negative copper, of which the bus-bar is grounded.

Fig. 7 gives the relative leakage currents with the bus-bar insulated.

Fig. 8 gives the relative leakage currents for Case VII with bus-bar insulated, plotted with the number of feeders as abscissas, the points representing half feeders being as explained above.

It is at once apparent that insulating the negative bus-bar very much decreases the leakage current in all cases, the reduction being in the neighborhood of 80%. Further than this, it is unnecessary to consider the case of a solid ground at the power station.

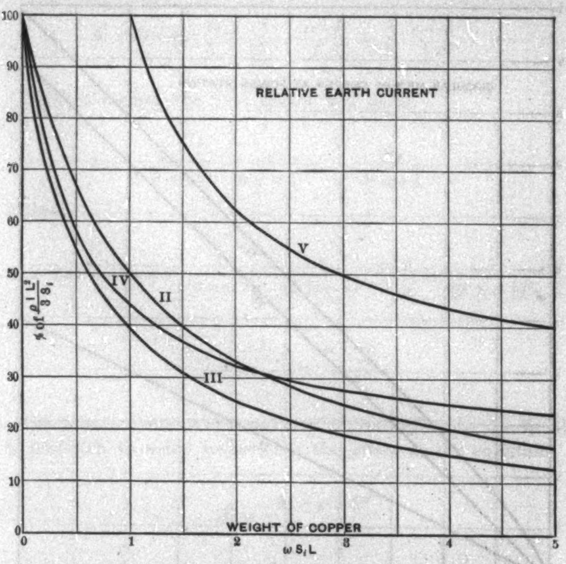


FIG. 6.—Relative earth current. Negative bus-bar grounded.

With the bus-bar insulated, it is seen that the leakage currents with copper distributed either uniformly or for uniform drop, are identical. The equations do not represent the same line but they agree so nearly that the curves are identical within a very few per cent.

With a single feeder to the middle of the line and a connection to the bus-bar at the power station, it is seen that for large feeders, the results are poorer than for any other method, the divergency becoming greater as the amount of copper is increased; but with a single feeder and no other connection between bus-bar and rails, the leakage is independent of the amount of copper used and equal to 4.8% of the original leakage with the bus grounded and no copper in the negative circuit.

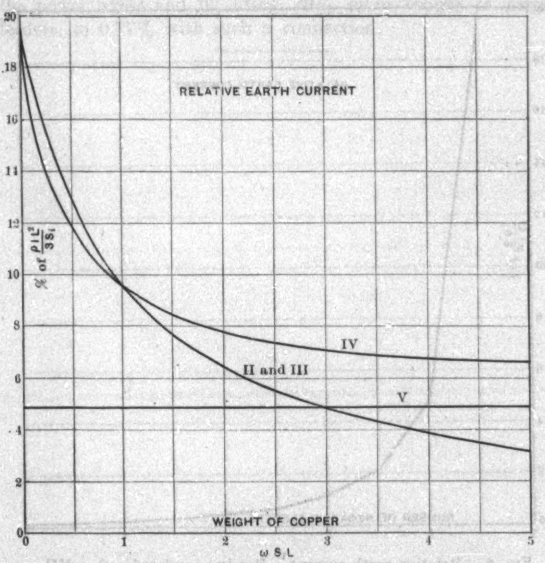


FIG. 7.—Relative earth current. Negative bus-bar insulated.

This latter is really covered by Case VII. The great superiority of the boosted negative feeder method of reducing earth currents is at once apparent, two feeders reducing the leakage to 1.2% of its original value with the bus-bar grounded, or about 6.2% of its original value with the bus-bar insulated. Very little is gained by using more than two feeders.

In conclusion, a few figures as to the amount of copper required to reduce the leakage to one half with the bus grounded may be of interest. Let us consider a double-track road with 100-lb. rails. The equivalent conductivity of each rail is about 1,200,000 cir. mils of copper if well bonded, making $s_i = 4,800,000$.

If the copper is to be of uniform section 4,800,000 cir. mils must be used the entire length of the line.

If the copper is to be distributed to best advantage it must be of a section 9,120,000 cir. mils at the power station, being reduced uniformly to zero at a point 65.5% of the distance to the end of the line. The total amount of copper used will be 62% of that in the first case.

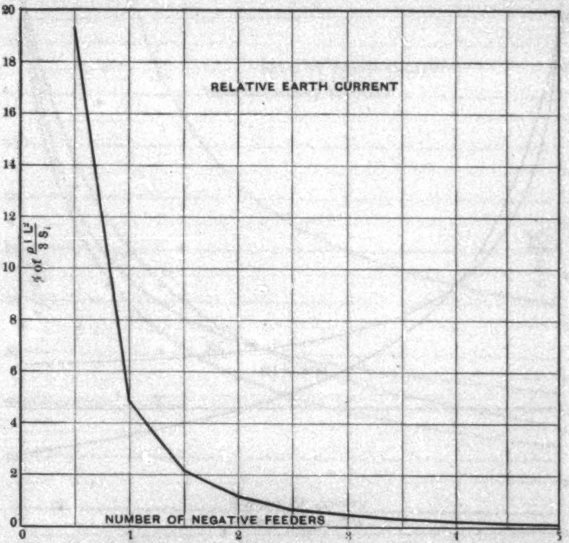


FIG. 8.—Relative earth current. Bus-bar insulated.—Case VII.

If an insulated feeder to the centre of the line is used, with a connection at the power house it must be of a section 7,200,000 cir. mils making the weight of copper 75% of that in the first case.

If the bus-bar is now insulated the 4,800,000 cir. mils of copper extending the entire length of the line will reduce the leakage to 9.7%; 62% of this copper distributed to best advantage will reduce the leakage to 12%; while a single feeder with a connection at the power house, using 75% of the copper will reduce it to 10.4%. Using a weight of copper determined only by its carrying capacity and the cost of power, in two boosted feeders, will reduce the leakage to 1.2% with no connection at the power house and by using 20% more copper in longer feeders, to 0.77% with such a connection.

DISCUSSION ON "ELECTROLYSIS," AT NEW YORK, MARCH 1, 1907

L. B. Stillwell: The results of Mr. Hayden's comprehensive and painstaking tests are particularly gratifying to all interested in the extensive use of electricity for railway purposes. While they show, however, that the electrolytic damage to subsurface metallic structures which alternating currents are liable to cause is practically negligible under ordinary circumstances, they illustrate also the fact that here, as elsewhere, special conditions may exist which call for the adoption of preventive measures. The method of protecting cable sheaths which Mr. Hayden suggests is ingenious and interesting. Quantitatively considered, however, his results indicate that it will rarely be necessary to adopt his plan of superimposing a continuous potential upon an alternating potential.

Mr. Knudson's paper and that of Mr. Rhodes have to do with electrolysis by continuous current. This subject is an old one and in the nature of things it is always with us. Unfortunately in its discussion the lawyer generally has been rather more prominent than the engineer. Too often also the engineers who have been retained by one or the other parties interested in litigation or threatened litigation, over actual or alleged damage by electrolysis, have approached the subject from a radically partisan viewpoint. Engineers representing the owners of water pipes or gas pipes have seriously recommended that street railway companies should be compelled to provide complete metallic circuits for their current, absolutely insulated from rails and ground. On the other hand, street railway companies, in many instances, have installed their plants apparently with absolute disregard of the effect of stray current upon the property of their neighbors; even going so far as deliberately to connect their track return to lead service pipes wherever opportunity offered.

Engineering is applied science; science is knowledge of facts. Nowhere better than in the meetings of this Institute can the essential facts ascertained by experiment or deduced by correct theory be discussed frankly and fairly, and nowhere better can engineering methods minimizing or preventing damage be worked out in a spirit of fairness to all concerned.

In the suit of the city of Dayton against the street railway company for alleged damage to water pipes owned by the city, Judge O. B. Brown in rendering his decision, admirably stated the rights and duties of the respective parties in the following words:

> The use of the streets for water works purposes is obtained by legislative authority. The right of an electric railway to use the streets is from like authority. Each of these uses is beneficial to the public and each is entitled to use its respective rights, without interfering with the other, and it is clear that no conflict can occur between the two if each would remain within its own sphere and exercise its powers with

> due care and prudence. It is not necessary in arriving at a proper decision in this case to determine which should give way to the other. Both are legal, and both are important and of almost equal necessity to the inhabitants of the city.
>
> * * * * * * * * *
>
> Each should exercise its functions for the general good, exercising due care not to interfere with the duties and rights of the other.

There can be no question that in many of our cities and towns damage due to electrolysis is in progress which might be prevented by reasonable application of known principles and methods. That the prevention is not employed is due, in part, to our engineers, but perhaps still more to the general unwillingness of the management of electric railway companies to spend money in preventing damage which is not seen. This unwillingness to incur expenses in correcting conditions not realized by the executive management of the companies is naturally to be expected. The duty of the engineer is to exercise his influence to secure a realization of the fact that an ounce of prevention is worth a pound of cure, and to induce his client to take timely precautions to protect the interests of his neighbors, and, by so doing, to protect his own.

Mr. Rhodes' paper is an excellent theoretical discussion of the possibilities of an apparatus probably destined to do much more work in the future than it has in the past. Properly applied, it is of the greatest value in minimizing electrolytic damage under certain conditions. The plans of the Hudson companies contemplate the use of boosters to prevent possible electrolytic damage to the metallic shells of the tube tunnels destined to connect the Borough of Manhattan and the New Jersey shore. The Interborough Rapid Transit Company is also proposing to use them for a similar purpose in connection with its tunnels under the East River.

While the papers of Messrs. Hayden and Rhodes are convincing and of special value, that of Mr. Knudson would seem decidely to require revision of methods employed before satisfactory conclusions can be drawn. As regards Fig. 6 of this paper, the method employed; namely, the increase of potential to keep current constant, notwithstanding the apparent tendency of the reinforced concrete to protect itself, seemingly makes the conclusions reached of little value. No proof whatever is presented that the splitting of the concrete blocks was due to electrolytic action, as no effort had been made to exclude other possible causes, for example, expansion due to chemical change in the concrete itself. It is important to ascertain the facts as regards electrolytic corrosion of iron or steel in concrete, but the paper as presented fails to establish them.

Frank N. Waterman: We all know that electrolytic phenomena are so essentially mysterious to the average mind that it is almost impossible for the public to distinguish between true statements and false. Electrical engineers should, therefore, be extremely cautious about making statements that might mislead the layman. It is therefore peculiarly important that the discussion of the subject by the Institute should be careful and scientific, since its utterance will be regarded as authoritative. The papers by Messrs. Hayden and Rhodes are most gratifying in this respect, but the paper by Mr. Knudson contains much that cannot be considered as the last word on the subject.

Iron encased in concrete is like a battery electrode in a porous cup so far as insulation is concerned; of course current can be sent through it, and it can be made to take iron with it. Cement as a protector of iron acts both mechanically and chemically. If a current is introduced into the midst of it no protection is to be expected, unless by chemical action with the initial products of the decomposition a protective or highly resistant coating is formed which will restrict the flow of current. In Mr. Knudson's paper five samples of cement were used, but the author has not told us about the physical or chemical properties of the cement, how long it had been cast, or its age or condition when cast. Whether it contained free lime tending to make it develop expansion cracks, or whether its constitution predisposed it to shrinkage cracks, are not set forth. These facts are important, and should be carefully considered in accounting for the cracking of the blocks.

I should like to know the condition of the iron surfaces before weighing and casting—whether they were turned or filed bright or were coated with oxide grease and dirt; and, too, did the same person that did the original weighing do the final weighing? And how was the cement removed from the iron surface? It appears that the coating on the surface was not dissolved off but was scraped, in the case of the samples subjected to current, while the single specimen not subjected to current was not scraped. Therefore, I think it would be interesting to learn how much of the material set down as loss was original oxide and dirt, how much was natural corrosion, and how much good iron filings? The maximum depreciation as given is about 1.5 oz. in 3 lb. 7 oz., or less than two-thirds of the expected loss.

In the passage of current through the samples, Mr. Knudson says that a constant current was sent through, the voltage being remorselessly raised 1400% to effect the result. It seems to me that the raising of the voltage to that extent would in itself baffle the efforts to determine the utility of cement as a protector.

We are told that the cement cracked, it would be interesting and valuable to know whether a current will have such an effect on cement and if so to what particular action or influence it is due.

Fig. 6 suggests that the samples subjected to current very soon began to protect themselves, and that to maintain the current flow, the voltage had to be raised to 42 volts, or 14 times the minimum energy; that is, to 4.2 watts. The surface of the pipe was about 0.45 sq. ft. or about 9.5 watts per square foot of iron if the resistance was concentrated at the surface. In the case of the salt-water specimen it seems that the voltage was increased 5.5 times.

Were these tests made with regard to temperature or the rise of temperatue due to the current? This, I think is worth considering, as the energy was so large as to cause foaming and evident heating.

So far from indicating that iron encased in concrete will be injured in practice, these curves seem to suggest that had the samples been subjected to anything like natural conditions they would promptly have protected themselves against damage. Under such conditions, voltages are not raised to many times normal values in order to force a definite current through; temperatures are kept at low and relatively constant values, the opposite electrode is not usually brought up to within a few inches of the iron, and the current concentrated along a radial line through the concrete as in these experiments.

If iron will protect itself against electrolytic action when encased in concrete, as the paper seems to indicate, the fact is interesting and important. If, on the other hand, it will not be materially protected, that fact is also interesting and important. But the paper gives us no basis for a positive opinion. The measurements seem to indicate that the iron will tend to protect itself, but unfortunately the method of experiment makes it quite impossible to say whether it will or not.

The author's conclusions on these experiments are most sweeping. Thus he concludes:

> If but a small fraction of an ampere of electricity passes from an interior metallic column or structure into concrete or masonry as usually made, there will be corrosion of the metal and disintegration of the concrete or masonry.

What the author calls a small fraction of an ampere amounted in fact to nearly 0.25 ampere to the square foot, or for the sake of comparison to 5,000 amperes per mile of 30-in. water main; in other words, a current which is extremely large compared with those likely to exist in practical conditions except under very exceptional circumstances. There does not seem to be any ground for the assumption that the current had anything to do with the cracking of the concrete, much less that it would under practical conditions have such an effect.

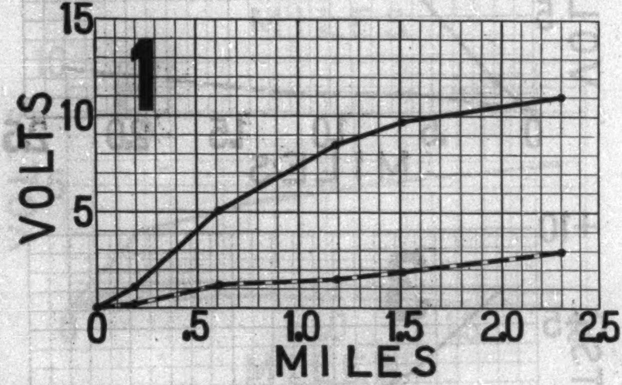
We are shown a picture of a corroded water-meter, but just what a corroded water-meter has to do with the subject of the paper is not quite clear. That an iron shell resting on the earth floor of a damp cellar for a sufficient period will be destroyed whether there is electric current in the neighborhood or not, is well known. Not the slightest proof is offered that this sample was in any way affected by current.

One thing in Mr. Rhodes' paper seems to me a very picturesque way of stating what all of us have encountered; namely, the enormous quantity of copper required appreciably to reduce the drop where the feeders parallel the track. The unit which he takes is the weight of copper of conductivity, equal to that of the rails. It is an impressive thing when one has had occasion to figure what that means. The natural result in such cases, where reduction of drop is necessary, is the negative booster. Unfortunately, we do not deal with the negative booster on the simple lines of the paper. We are not given roads which run straight from the power-house, and are uncomplicated by branches or network. Some systems can be reduced to a plurality of such lines, but the majority will involve a more or less complicated network. The distribution of current in a network is determined by constantly changing bond resistances, particularly where special work is not kept up. The negative booster offers an extremely interesting possibility in that connection. It gives the means, with reasonable watchfulness, of controlling the distribution of current in that network. The paper dealing as it does only with the single-trolley line, naturally does not bring that out. It shows the enormous gain in respect to reduction of earth currents, but does not show the other possibility of the negative booster; namely, the control of the distribution of the return current in the network, which is a feature in many cases of very great value, particularly in making it possible to reduce to a minimum the track drops in those regions where such current, as has escaped to the earth, is returning to the rails, thus giving a current density of minimum value in the pipes, at points where current is leaving them, that is where they are positive to the rails.

Paul Winsor: We think we have a pretty good railroad in Boston; well bonded, a good deal of return copper, and we follow it pretty closely. But in certain places we have bad conditions; the trouble we have had, unknown or unlooked for trouble, has taken place near the Harvard power station, where there is a marsh of salt water, and beyond which, about a mile away, is the first car track in that direction. A large number of water mains are located near by, but a careful study of the situation has reduced the electrolytic trouble most materially. The telephone people have taken great pains to survey their cables, and when they find a place where they think there is danger of electrolysis, they consult with our engineers, and we put in either a negative feeder or a connection to our rail. This removes the trouble. On our own cables we have cut the lead in many places, made special connections, and got rid of the trouble. The Metropolitan Water and Sewerage Board have some large pipes running into Boston. We studied the matter carefully with them, and finally put eleven insulating joints in those pipes. Some of the joints are of rubber, and some are of wood, ordinary bell and spigot joints, with ⅝ in. to ¾ in. of pine calking.

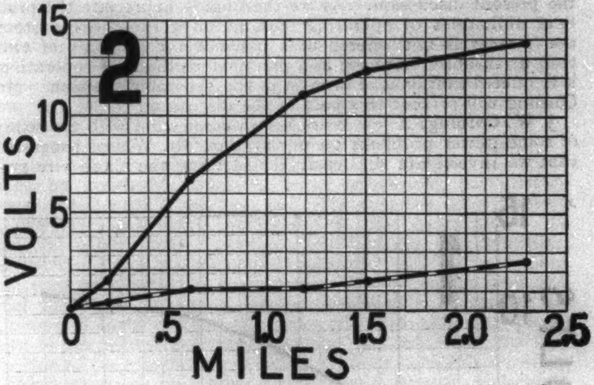
Some time ago we made some experiments in operating certain portions of our road on the three-wire system. Some of the data we got regarding the current in the neutral back to the station; that is, the return currents through the rails and underground structures, seem to me of interest in connection with the present discussion. As we thoroughly appreciate the practical difficulties of operating stations on a three-wire system, the matter is not offered as a panacea for the cure of electrolytic troubles, nor even as a practical method of operating; it is offered simply as of interest in the general discussion. Mr. Corning will present this part of the discussion.

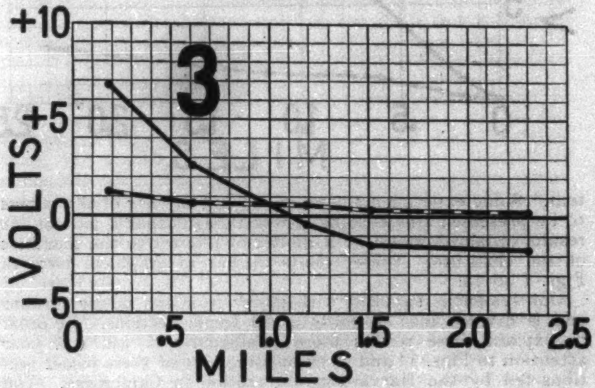
J. W. Corning: A few years ago in connection with the study of some power problems on our system, Mr. Winsor suggested that we investigate the feasibility of using the three-wire system. Some experiments were made, and in view of the papers to be presented this evening it was thought that a part of the results obtained would be a matter of interest to the members of the Institute. These results appear in graphical form in Figs. 1 to 15.



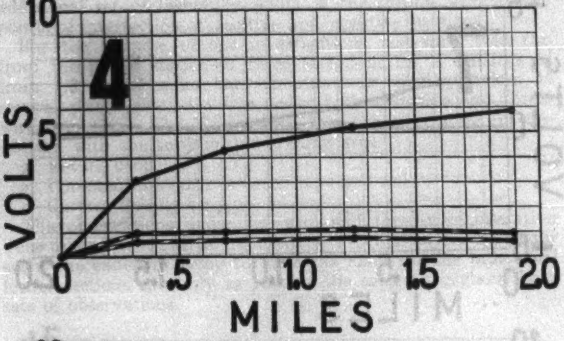
Our system is supplied with power from ten power stations and is divided into upwards of 70 feeder sections. In order to explain these results more intelligently, I will call your attention to Figs. 14 and 15 comprising nine of these feeder sections fed by the Harvard power station in Cambridge. You will notice from these maps that the dash lines indicate the boundaries of the feeder sections, the numbers of which appear. The heavy lines indicate tracks. Passing through this district from one side to the other will be seen depicted some 48-in. water mains. The power station location is indicated by the star (*).

We operate on the two-wire single-trolley grounded-return system. Fig. 14 represents the ordinary relation between feeder sections with this system. Referring now to Fig. 15, it will be noted that certain of the feeder sections have been shaded.





In the experiments referred to, these sections were supplied from this power station by current from a generator connected in three-wire relation with the rest of the station. No line change was made in the feeder sections beyond installing an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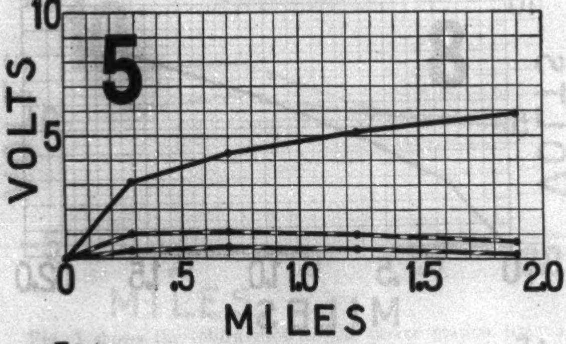
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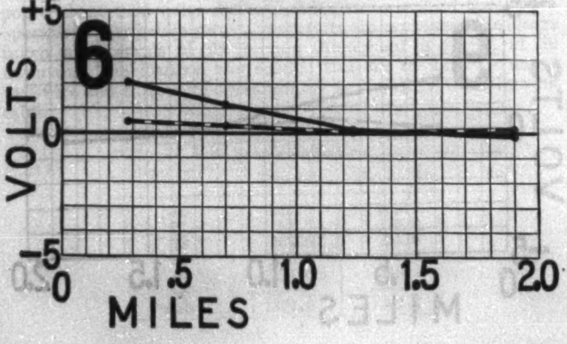
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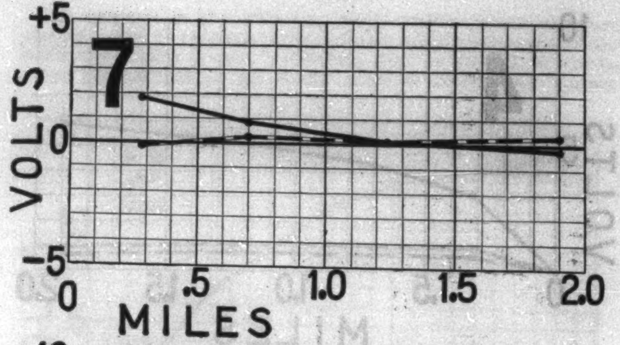
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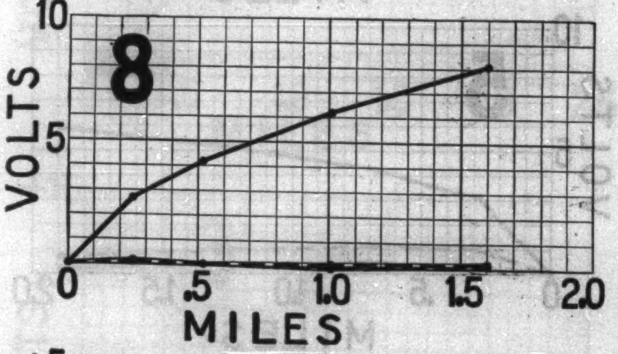
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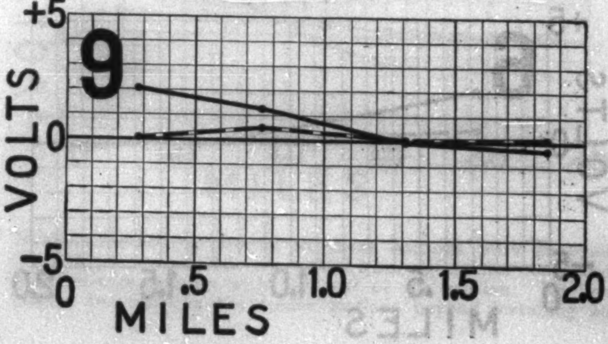
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additional set of insulating joints in the trolley wire at the points of intersection of positive and negative sections.

For the purpose of our investigations, test-wires were run from the power station in three directions for a distance of from 1.5 to 2.5 miles, and simultaneous readings taken at several points along the line, under both two-wire and three-wire operation. The observations that are interesting in connection with the subject this evening are:

a. Return drop,
b. Potential difference between pipe and rail.
c. Current flowing on pipe.

The observations under two-wire and three-wire operation were taken about two hours apart for a period of one-half hour each, the endeavor being to have the loads on the individual feeder sections as nearly as possible the same throughout both sets of observations.

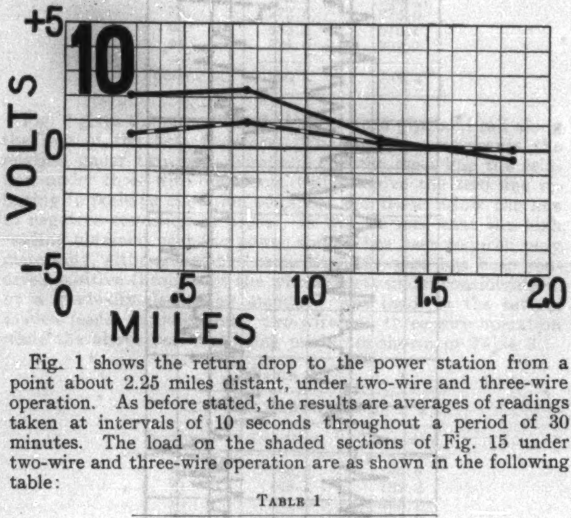
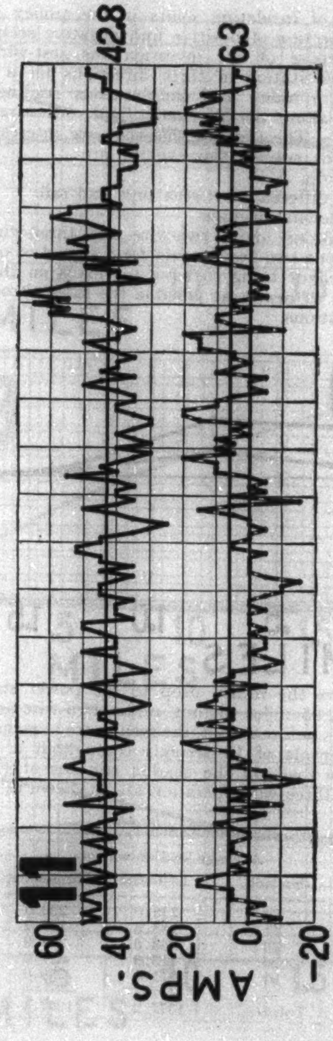


Fig. 1 shows the return drop to the power station from a point about 2.25 miles distant, under two-wire and three-wire operation. As before stated, the results are averages of readings taken at intervals of 10 seconds throughout a period of 30 minutes. The load on the shaded sections of Fig. 15 under two-wire and three-wire operation are as shown in the following table:

TABLE 1

Average load on section.		
Section.	Two-wire.	Three-wire.
70	246.0	222.0
71	183.6	133.2
73	263.6	251.9
90	413.0	411.0
91	271.0	249.0
Totals.....	1377.2	1267.1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42.8
6.3
60
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20
0
-20
AMPS.

From this table it will be seen that the conditions with respect to load are almost identical in both cases. It will be noted that the return drop under two-wire operation, represented by the full line, was reduced to that under three-wire operation, represented by the dash line, the drop throughout this length being reduced by about 83%.

Fig. 2 gives the results of a test which was repeated on another day in which practically the same results were obtained. The following table gives the loads in the several feeder sections:

TABLE 2

	Average load on section.	
Section.	Two-wire.	Three-wire.
70	278.3	305.2
71	196.9	303.2
73	272.6	275.0
90	488.0	516.0
91	325.0	339.0
Totals.....	1560.8	1738.4

Fig. 3 gives the potential relation between pipe and rail along the line of the first test-wire. The full line represents the relation under two-wire operation, and the dash line the relation under three-wire operation, values above the zero line referring to positive condition of pipes, and those below the line to negative condition of pipes. It will be seen that the high reading obtained near the power station has been reduced very materially, although at the same time the pipe has been rendered positive throughout the whole length under consideration, by a gradually decreasing amount. The loads in the several shaded feeder sections under two-wire and three-wire operation while the above test was being made are shown in Table 3.

TABLE 3

	Average load on section.	
Section.	Two-wire.	Three-wire.
70	245.2	266.6
71	145.2	189.2
73	231.0	295.2
90	524.0	527.0
91	378.0	329.0
Totals.....	1523.4	1607.0

Figs. 4, 5, 6, and 7 give results obtained along the second test-wire. Figs. 4 and 5 show return-drop relations on two different days. The current relations in the several shaded feeder sections for Figs. 4 and 5 are as shown in Tables 4 and 5

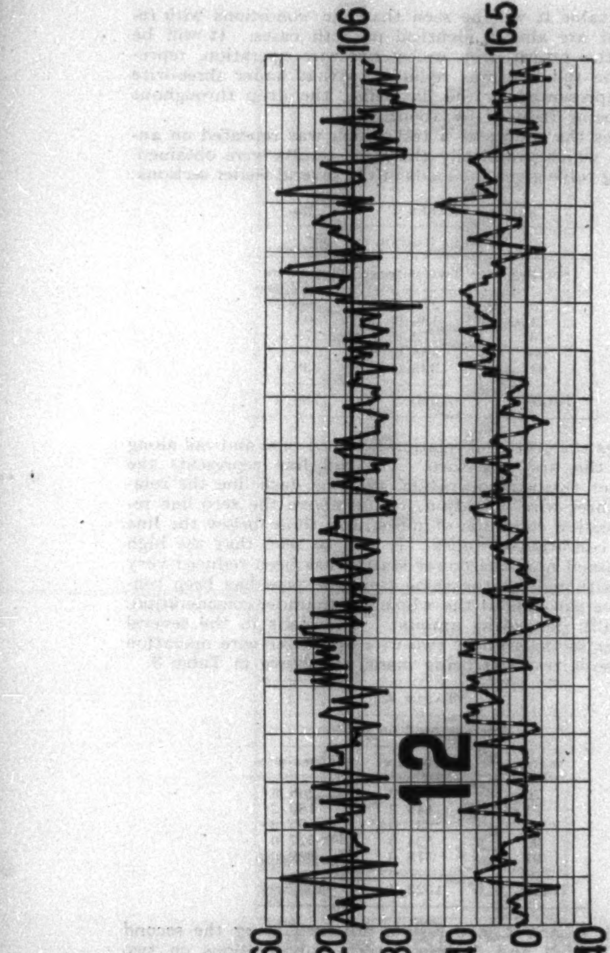
106
16.5
12
160
120
80
40
0
-40
AMPS.

TABLE 4

Average load on section.		
Section.	Two wire.	Three-wire.
70	215	208
71	136	149
73	241	262
90	480	454
91	266	300
Totals.....	1338	1373

TABLE 5

Average load on section.		
Section.	Two-wire.	Three-wire.
70	224.6	181.9
71	152.6	134.6
73	232.4	232.6
90	455.6	464.0
91	264.0	302.0
Totals.....	1329.2	1315.1

Attention is called to two sets of results, in each case under three-wire operation. While the upper set of observations was being taken, section 70 was feeding in the usual manner; whereas, while the lower set of observations was being taken it was fed from the other side of the three-wire system.

Figs. 6 and 7 show the potential relations on the pipe along the line of the second test-wire under two-wire and three-wire operation, and it is clearly seen that in these cases the potential differences between pipe and rail have been almost eliminated. The load relations of the sections while these observations were being taken are shown in Tables 6 and 7

TABLE 6

Average load on section.		
Section.	Two-wire.	Three-wire.
70	234	199
71	113	111
73	284	285
90	445	404
91	249	277
Totals.....	1325	1276

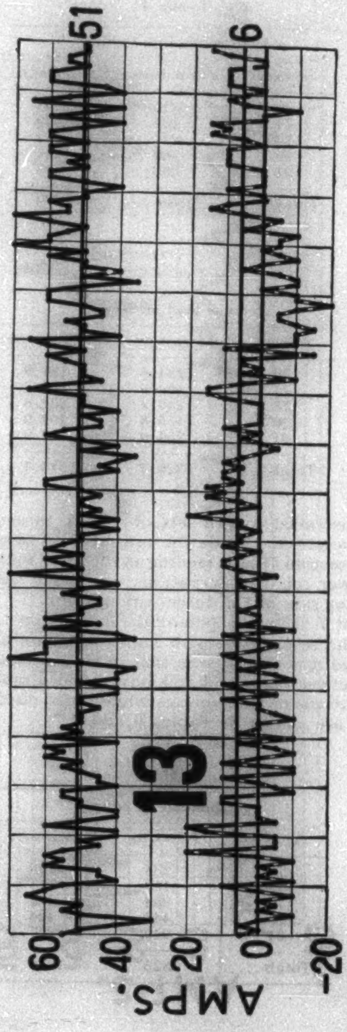
51
6
13
60
40
20
0
-20
AMPS.

TABLE 7

Average load on section.

Section.	Two-wire.	Three-wire.
70	205	267
71	190	199
73	301	235
90	488	536
91	384	370
Totals.....	1568	1607

Fig. 8 gives the return drop along the line of the third test-wire. While the three-wire system was in operation, section 70 was fed part of the time from one side and the rest of the time from the other. The results are as shown. It will be seen that the return drop in this case was practically wiped out, the three-wire potential curve practically coinciding with the zero line. The effect of reversing section 70 in this case was not as great as it was in the last instance, but is just noticeable. The load on the several sections while these results were being taken is shown in Table 8:

TABLE 8

Average load on section.

Section.	Two-wire.	Three-wire.
70	286.	321
71	170.6	199
73	280	236
90	627	600
91	372	380
Totals.....	1735.6	1736

Figs. 9 and 10 show the effect on the pipe potential in this district of three-wire operation, as compared with two-wire operation, and similar relations of potentials are observed as have been observed in the previous cases.

I would now call your attention to Figs. 11, 12, and 13, which show readings of current flowing on the large mains which traverse the district in question, under two-wire and three-wire operation. These readings were taken for a period of 30 minutes at intervals of 10 seconds. It will be seen in Fig. 11 that under two-wire operation the average current flowing on the pipe was 42.8 amperes, with a maximum of 70 amperes. Under three-wire operation this current was reduced to an average of 6.3 amperes, and a maximum of 20 amperes. On Fig. 12 an average current of 106 amperes, with a maximum of 155 amperes is reduced by three-wire operation to an average of 16.5 amperes and a maximum of 55 amperes. In Fig. 13 an average current of 51 amperes, with a maximum of 70 amperes under two-wire operation, is reduced by three-wire operation to an average of 6 amperes and a maximum of 20 amperes. The results in each one of these last three figures were taken at a different point on these pipes, the current being calculated from the resistance of the pipe, and the potential drop along a single length, not including joints. In the case of the three-wire operation, the averages given are averages of all observations, those below the line being taken with a positive sign. In these three cases the three-wire operation shows a reduction in current flowing on the pipe of 85, 85, and 88% respectively.

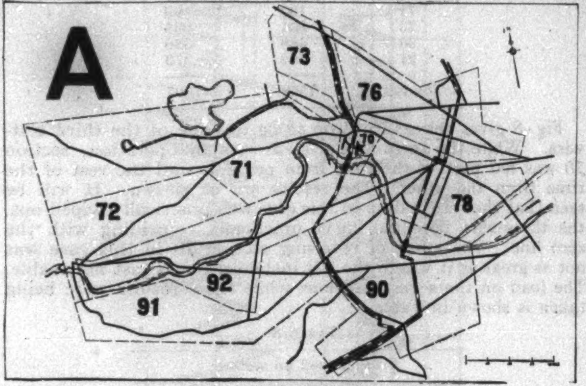

FIG. 14.

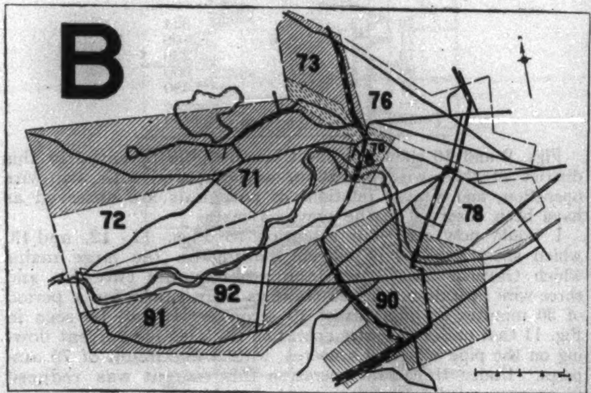

FIG. 15.

S. M. Kintner: It is satisfactory to find that the results of Mr. Hayden's tests agree with the results of tests that I made some two or three years ago.* I made tests quite similar to those reported by Mr. Hayden, though not so many different kinds of solutions were tried. The laboratory tests showed the following results:

1. That the loss was not directly proportional to the ampere-hours, as repeated weighings of the same plates after equal ampere-hours of current action failed to show equal losses.

2. That the shape of the plates had a very decided effect upon the results obtained, the edges being by far the most active part of the terminals. The best results were obtained with terminals mounted so as to form two sides of the box containing the electrolyte, the rest of the box being of impregnated wood The terminal plates were approximately six inches square.

3. That it was necessary to have a duplicate cell for every one subjected to the alternating-current electrolysis, the duplicate being used to determine the chemical action alone. Attempts to reduce the corrosion loss to so much per unit surface, and thus correct for losses in various size cells, gave very inconsistent results.

4. That the loss on the so-called "gain plate" of a cell in which a sodium chloride solution and iron terminals were used, when subjected to the action of a direct current, was greater than the losses on similar plates subjected to alternating currents.

5. That the residue in cells, such as the last described, showed a very marked difference when analyzed chemically. The analyses of residue for the cells subjected to chemical corrosion only, and those subjected to the alternating current action, were very similar, while that of the direct current cell was very different.

Laboratory experiments in which cells were used were carried on for several months, with results somewhat similar to those obtained by Mr. Hayden. The broad general conclusions reached were that:

a. For iron and steel there was in general little or no loss greater than the chemical corrosion.

b. But for lead and tin-lead, such as employed in cable sheaths, there was a slight loss which varied from one quarter to one half of one per cent. of what would be obtained from direct current under similar circumstances.

A long-time test was then undertaken in which pipes of from 4 to 6 feet in length were buried for a period of one year. During all this time an alternating current of 25 cycles and 25 volts was applied between each pair of pipes. In this test, pairs of pipes of wrought iron, cast iron, and lead were used. Each pipe was carefully weighed and marked before it was buried, and was weighed again after one year's test. The losses in weight of the several pipes were not materially different, it being on the average the same for the pipes subjected to the alternating current as for those subjected to corrosion only. It is believed that a test of the kind just mentioned is much more representative of operating conditions than any that can be carried out in a laboratory.

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*Electric Club Journal, November, 1905.

Careful visual inspection of the pipes as they were removed from the ground failed to show any difference between those subjected to the alternating currents and those which were not.

Referring to Mr. Hayden's conclusions regarding the electrolytic effect of current densities in amperes per square foot, I think that the current densities mentioned by Mr. Hayden are very unlikely to exist in actual service. I found that it required about 260 volts to force only 30 amperes of current between two terminals each of 20 square feet of surface. The terminals were only 6 feet apart and the earth was exceedingly moist; the water was also very impure, as a large part of it was surface drainage. Another test with similar size terminals placed in a less favorable location gave only about 7 amperes for 260 volts. It is the writer's opinion that the alternating current, so far as practical service conditions are concerned, will not cause serious electrolytic damage to pipes.

Calvert Townley: With reference to general electrolytic problems, I think we have all been too much afraid of them. When attacked with the same vigor that is commonly brought to bear on other problems connected with the generation and distribution of electricity, electrolytic questions show themselves no more difficult of solution. While not desiring to belittle the damage which may occur from neglect to take proper precautions against the electrolytic action of direct currents, I do think it is time to discourage giving them disproportionate importance, and timidity in their handling. The public has been led to believe that electrolysis going on secretly and continuously under our feet is much to be dreaded; but if those who have to do with underground structures liable to electrolytic attack, and those who have to do with the generation of current which is likely to attack such structures, will jointly take pains to ascertain by suitable measurements what the existing conditions are, and will take such reasonable precautions to minimize the troubles as the state of the art permits, I believe that the seriousness of the situation will be largely, if not entirely, eliminated. As engineers, our efforts should be to bring the facts before all interested parties, and let it be known that, treated intelligently and carefully, electrolytic troubles can be largely prevented.

I get much encouragement from Mr. Hayden's paper. I have not known much about alternating-current electrolysis, but have had a general feeling that it was insignificantly small. Mr. Hayden's paper, as well as Mr. Kintner's discussion, greatly strengthens this feeling. As far as I know, there is yet to be reported the first case of trouble anywhere in practical service from electrolysis due to alternating currents.

I understand that in protecting the lead sheathing of their cables from direct-current electrolysis, the telephone companies have adopted a method which they have found to be entirely satisfactory; namely, where the cable is positive to the return circuit they connect the lead sheath of the cable to that circuit by a metallic conductor or bond, so that any difference of potential that may exist between the lead sheath and the return circuit is practically eliminated. No attention is paid to the sheath where it bears a negative relation to the return circuit; that is, where the tendency of the return current is to flow from, say, the rail of a trolley road to the sheath. But where the tendency of the current is to flow from the sheath to rail, and electrolytic damage may occur in consequence, a bond is inserted. Now the tendency to flow from sheath to rail is not concentrated at any one point. The positive relation frequently extends over a considerable area, although practice has shown that electrolytic damage may be prevented by the insertion of a bond only at some one central location. Obviously, it follows, therefore, that the additional drop in the lead sheath from the outlying territory of the positive area to the central bond can be neglected, although in many cases it must represent an appreciable potential. Mr. Hayden has shown that under the most unfavorable conditions, alternating-current electrolysis will not exceed one per cent., and will seldom equal as much as one-half of one per cent. of the electrolytic action of the direct current of like volume.

In the light of the foregoing, then, it becomes pertinent to inquire whether the total tendency towards alternating-current eletrolytic action is any greater than the residual tendency for such action from direct currents in outlying parts of the positive district, and which it has been found are practically negligible. I think we can all take a great deal of encouragement from the very small amount of electrolytic action found to take place under the most unfavorable conditions of Mr. Hayden's test, and from the interesting comments contained in Mr. Kintner's discussion.

George F. Sever: It is fortunate that we should have so valuable a discussion on this subject from Boston, because our first real knowledge of electrolytic troubles came from Boston some years ago through a valuable paper by Mr. Farnham.* He investigated this subject most thoroughly in the interest of the telephone company, and the West End Railroad of Boston, now the Boston Elevated, assisted him materially in his investigation. Since that time, the subject has been very carefully followed up in Boston, as well as in many other places.

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*TRANSACTIONS, A. I. E. E., 1894, Vol. xi., p. 191.

If the interests in all other cities, such as New York, Philadelphia, Chicago, St. Louis, and Pittsburg, should study this question from an engineering standpoint, we would have but little contention as to the proper methods to apply in remedying the supposed difficulty.

I speak from the standpoint of a municipal engineer, who finds in his city some isolated indications of electrolysis. The engineer, whether he represents the water or gas interests, reports this difficulty, and possibly a suit against the local railroad company results. If the court reaches any decision, whatever it may be, there is no assurance that sub-surface conductors are not incurring further damage In my opinion—and I have carried this out in practice in the city— the only way to handle the situation is for all parties in interest, with their engineers, to agree upon a policy, and to study the situation carefully and together, and endeavor to reduce the difficulty wherever it appears. I think we make too much of electrolytic troubles; I think those who stimulate this idea in the minds of engineers do not realize what electrical engineers can do to remedy the supposed difficulty. Some time ago the American Water Works Association published a long and interesting report signed by three eminent engineers, recommending that every trolley road in the country be changed from the single overhead trolley system to the double-trolley system, as a sure remedy for electrolytic troubles. That interesting document is referred to in almost every electrolysis case; having the opinion of these three eminent engineers behind it, it is very impressive to the authorities. I think the Institute should take some recognition of this report, to the end of pointing out that the electrical engineer, in coöperation with the municipal engineers or water works engineers, can mitigate and cure the difficulty. In one city that I know of, the water system is supposed to be undergoing continuous damage, whereas the gas system owned by the city has not indicated that any damage is occurring to its system.

Mr. Hayden's paper prompts me to cite the result of some tests and investigations made at Columbia University in 1904, on alternating currents as producing electrolytic action. At that time we had available only 60-cycle current. We arranged cells containing certain solutions such as sulphates, chlorides, carbonates, and nitrates of different metals, and passed current through them by means of lead plates. From the results obtained we arrived at the following conclusions:

1. That alternating currents can cause a slight electrolytic action. 2. That the rate of this action is very much slower than with direct currents of the same value. 3. When insoluble or semi-soluble salts are formed, the rate of action with a given current strength decreases with the passage of time. 4. That the resistance of the cell decreases with increasing current strength for alternating current as well as for direct current.

5. That the resistance is not only in the liquid itself, but particularly in the contact layer where the electrode and electrolyte meet.

Variations in the density of the current, or of the electrolyte, unless excessive, have no marked effect. Unless subsequent investigations shall bring to light differences likely to exist in the earth, in which corrosive action is more vigorous than between lead and the common salts of the alkali metals—and no such combinations are known as applied to direct-current railway operation—the corrosive action of alternating currents on sub-surface metal structures may be assumed to be negligible. This investigation is being supplemented by a further one for lower frequencies, and I trust we shall be able later to report the results of that investigation

Albert F. Ganz: The experiments described by Mr. Hayden show that with an alternating-current electrolytic corrosion is generally a very small fraction of that which would be produced by a direct current of the same strength and under the same conditions. The action is explained by the statement that the corrosive effect of the positive half wave of current is not entirely reversed by the reconstructive action of the succeeding negative half wave. The reason for this lies probably in the fact that a portion of the products of the electrolysis, produced by the current during the positive half cycle, diffuses away so that the negative half wave of current does not quite reverse the action of the positive half wave. Since these rates of diffusion vary greatly with different materials, the per cent. of direct-current electrolysis produced by an alternating current varies greatly with different electrolytes. On this theory the effect of increasing the frequency would be to diminish the electrolysis In general this has been found to be the case. The rate of diffusion of the products of electrolysis in the case of metals in the soil may also be governed by other conditions, such as by the amount of moisture present, temperature, etc., and this would seem to be so judging from the widely varying quantitative results which have been found by different investigators.

The suggested protective measure of superimposing a small direct current upon the alternating current so as to add to the effect of the negative half wave sufficiently to neutralize completely the corrosive action of the positive half wave is certainly very interesting, but does not seem to me to be a desirable thing to do in practice, as I understand the proposition, because it would mean deliberately to send a stray direct current through the ground and to have this enter the metal to be protected and return by way of this metal. This stray direct current, while small in percentage of the alternating current to be counteracted, in its passage through the ground may in itself be a source of electrolytic danger to other underground metal.

Referring to Mr. Knudson's paper, the curve shown in Fig. 7 is of importance inasmuch as it shows that concrete absorbs a considerable quantity of water and becomes an electrolytic conductor of comparatively low resistance, so that a few volts of electromotive force between a metal imbedded in wet concrete and the surrounding water or wet soil is sufficient to set up a current. It also explains why attempts to protect pipes from electrolysis by embedding them in concrete have failed.

Mr. Rhodes' paper brings out the very important fact that the disposing of return feeder copper is quite as important as the weight of return feeder copper used in the effort to minimize stray currents. The calculations given show, clearly that the way to obtain a minimum of stray current from the grounded rails of a single-trolley electric road is to insulate the negative bus-bar, and to employ two or more insulated return feeders either so proportioned in resistance or provided with negative boosters as to produce equal potentials at their connecting points to the rails. This method results in minimizing the potential differences in the rails, and for this reason also minimizes stray currents from the rails.

Mr. Rhodes assumes that the only resistance encountered is the contact resistance between the rail and ground, which is on the safe side. as it gives values for the stray currents which are too large; as a matter of fact the soil, especially when dry and sandy, has considerable resistance.

The question of electrolysis from stray railway currents has been very carefully investigated in Germany by a committee of the German Society of Gas and Water Engineers, who have already issued three annual reports. Translations of these reports for the years 1904 and 1905 are published in abstract in the *Report on Electrolysis* of the American Gas Light Association. The German committee have formulated a set of rules for electric trolley roads which are designed to prevent trouble from electrolysis due to stray currents.

These rules require permanent bonding of the rails so that the resistance of the finished track does not exceed the resistance of an equivalent unjointed track by more than 20 per cent. They also require that the resistance between the rail return and the ground be made as great as possible, and to this end forbid the deliberate grounding of the negative bus-bar and of any part of the return system. They also forbid the bonding of the rails to any underground pipes or other metals.

Great stress is laid in these rules upon the installation of return feeders in such a manner as to minimize the rail potentials; the following five of these rules relate directly to the return feeders and I will repeat them here because they bear directly upon Mr. Rhodes' paper:

3. *Potential difference in the rail network.* The potential difference in the rail network must be limited to a certain prescribed amount, which must not be exceeded with the greatest or most unfavorable loading of the return circuit.

The greatest permissible potential difference must be determined for each place separately, for it depends upon local conditions, such as the nature of the soil, the location and resistance of the pipes between points of highest and lowest potentials, the position of the pipes with respect to the rails, etc. In special cases, this greatest permissible potential difference may be different in different sections of a rail system.

For the present this maximum permissible potential difference in the rail network may be taken as *one volt*; this figure to be the average of readings for ten minutes during a period of full load.

4. *Return conductors*. Where the rails alone are not sufficient for the return current, without allowing the potential difference to exceed the prescribed amount, extra return conductors must be provided.

These return conductors must be so numerous and so planned that, in conjunction with good conductivity of the rail network, they prevent the potential difference in the rails from exceeding the prescribed amount.

The points where the return conductors are connected to the rails should be located as far from the pipes as possible.

The return conductors must be insulated and of sufficient size to return the current with only a small drop in voltage; so that, if an occasional change in the distribution of the currents occurs, no excessive difference in the potentials at the connecting-points of the return conductors will be produced.

The return conductors should have a cross-section at least equal to that of the outgoing conductors; where conditions require a number of return conductors, it may be better to make them of larger cross-section than the outgoing conductors.

6. *Adjustability of the return conductors*. An essential condition for minimizing the potential difference in the rails, and therefore the stray currents, is that the potentials be equalized at all points where return conductors are connected to the rails. The resistance of each return conductor must, therefore, be proportional to the strength of current which it has to carry. For this purpose, each return conductor must be provided with an adjustable resistance (or negative booster) so that the product of current and resistance may be made the same for all return conductors.

7. *Negative boosters* (*Sucker dynamos*). Negative boosters are to be recommended, particularly for the purpose of automatically regulating the rail potentials at the connecting-points of the return conductors in districts where the return conductors are liable to be frequently or seriously overloaded.

8. *Controlling arrangements*. Test wires must be led to the distributing station from all points where return conductors are connected to the rails, and from all points of relatively highest potentials in the rail network (points between two return connections and points at the end of the track). By connecting a voltmeter, it must be always possible to determine the potentials of these points in the rails. Arrangements must also be provided so that the current in any one of the return conductors can be measured at any time, etc.

The laying out of a proper system of insulated return feeders has been frequently neglected in this country, and even where insulated return feeders have been intsalled they have only in rare cases been properly proportioned for equal drop in potential. The usual method is to connect the rails with the negative bus-bar at the station with large copper cables, and in large installations to run out additional return feeders from these bus-bars to points on the rails distant from the station. The drop in potential in each of these long return feeders establishes points of higher potentials in the rails at these connecting points than exist in the rails at the station. The tendency is therefore for currents to leave the rails in these distant points of higher potentials, pass through the ground and buried metals, and return to the rails in the vicinity of the station.

Great improvements in the ground return circuits could generally be obtained in most of our trolley roads if these rules were followed at least to the extent of insulating bus-bars, removing all bonds to pipes, and installing a properly proportioned system of return feeders. The use of adjustable resistances in the return feeders is not a practicable arrangement for the large currents generally used on American roads. The use of negative boosters as suggested by Mr. Rhodes is, however, entirely practicable, and when applied with a judicious number of insulated return feeders will tend greatly to minimize stray currents. This is well illustrated by the curve in Fig. 8 of Mr. Rhodes' paper, which curve shows the percentage of stray current with various numbers of return feeders, and is based on the assumption of equal potentials at the connecting-points of these return feeders.

Mr. Rhodes says that very little is gained by using more than two return feeders. I do not believe that this is so on a large and extensive system. Referring to the curve in Fig. 8 it is seen that three return feeders will reduce by half, the stray current with two return feeders, and four return feeders will again reduce by half the stray currents produced with three return feeders. In a large system the stray currents obtained with two return feeders may still be a dangerous stray current making a larger number of return feeders imperative.

C. P. Steinmetz: Electrolysis is a branch of electrical engineering that has the misfortune to be of special popular interest. It has been exploited very thoroughly by the " yellow " press, gas pipes, water pipes, bridge piers—all these public and private utilities have been attacked and destroyed, in the newspapers, by this electrochemical phenomenon. Fortunately, iron is a material which is not so easily attacked by electrolytic action; wrought iron is not attacked very badly, steel very much less, and cast-iron is hardly attacked at all. For the electrical engineer, the problem of electrolysis is not the problem of protecting the rails —even the gas or water pipes can in general very well look out for themselves—for with a reasonable use of negative or ground feeders there is little danger. The greatest danger of electrolytic action is in the case of the lead cables of the telephone system. The underground metal structures which are suffering most, are the underground lead cables—the telephone cables. The power cables are relatively less affected, because they are better protected in subways, conduits, manholes, etc., and furthermore it is not economical to let a power cable lie idle. As long as it carries current it is at a temperature above that of the ground, and condensation is not likely to occur at or near it. But condensation and consequent electrolytic action do occur at or near a telephone cable.

The telephone companies have worked out, I understand, a system of protection by maintaining the cable negative against ground, by connecting it to the negative terminal. For this protection it is not, as was stated here in the discussion, necessary to see that no current passes between the lead cable and the rail. That cannnot be done, and current may pass; but the protection is perfect and absolute by making the cable throughout its whole extension more negative than the surrounding ground. As long as the lead cable armor is maintained at a potential, however slight, negative against the ground, there is no electrolytic corrosion, although current may pass. In this manner cables have been protected. Where no ground is used at the negative terminal of the dynamo, but only return feeders, by having negative feeders lead to the cables the whole cable system can be maintained at a negative potential against ground; even with a limited number of connections between the cable and negative terminal, the cable can be absolutely protected.

This shows the importance of considering alternating-current electrolysis. It has been stated in the discussion that alternating current electrolysis does not need to be feared, because it is less than one per cent. of direct-current electrolysis. I understand from those who know about the electrolytic attack, and the danger of it, with lead cables, that in many cases an electrolytic corrosion of telephone cables amounting to one-half per cent. of the direct-current action, would in a very short time be destructive. Therefore, fear is expressed that even with the greatly reduced electrolytic corrosion of the alternating-current the corrosion would still be destructive and harmful to telephone cables. It is said that against direct-current the lead cables can be protected, but against alternating-current it does not seem possible. This is the importance of the last section of Mr. Hayden's paper, which shows that even against alternating-current, lead cables can be protected. I believe that with the introduction of single-phase railways this protection will become necessary in many cases, even with an electrolytic action equal only to one-half per cent. of direct-current electrolysis.

It has been stated that the current densities in actual practice between cable and ground may not be as high as chosen in Mr. Hayden's tests. I beg to differ from that. If a cable is laid in the ground through its whole length, the total current from the cable to the ground distributed over the whole surface of the cable would give a low current density, but that is rarely the case with lead-covered cables. Laid in a conduit, the cable is, for most of its length, fairly well insulated from the ground, and it is only in isolated places where moisture condenses, or otherwise the cable comes in conducting contact with the ground, that current enters or leaves the cable to ground. In these spots the current density may be very high, and rapid destruction would take place if no protective action were resorted to. It is true that such a protective direct-current would somewhere else eat up the metal. But this is necessarily so, and when we protect lead cables against electrolysis by making them negative, it means that we prevent the electrolysis at one point by making it take place somewhere else. But this other place will be the rails which can stand it, because even with direct-current electrolysis the total amount of corrosion, when distributed over the whole extent of rails, in the rail return does not amount to anything compared with the mechanical wear. We may well neglect it altogether. It is only in the thin cable sheaths of lead cables at exposed places where damage may result, and the stray superimposed direct-current would not need to be feared in its electrolytic effect on the positive side of the rail return.

As stated, the problem is that of guarding against electrolysis of lead cables. Guarding against electrolysis of iron rails and gas and water pipes is not very difficult and with alternating-currents needs hardly to be considered, except in very extreme cases.

To protect against the alternating-current by a superposed direct-current may be done in the same manner as Mr. Rhodes has shown in his paper—lay out a system of negative feeders for an underground cable system, so as to insure that the total stray alternating current will be within the limits of protective action of the total direct-current superimposed upon it. I think that a further investigation similar to that given by Mr. Rhodes' paper may well be carried out and will result in an intelligent arrangement for protection of the lead cable system against alternating-current electrolysis.

Mr. Knudson's paper has been severely attacked, but it all depends how you look at it. I do not think that this paper can be considered as a conclusive decision on electrolytic corrosion of iron in concrete, but merely as some preliminary experiments which show that a further investigation is very desirable and should be made. All that the paper really shows is that a piece of iron in a concrete block is affected differently if a direct-current is made to flow, than if no current is made to flow. The next questions to answer would be: what is really taking place? How does it take place? What is the meaning of it? How can we guard against it? The paper does not state what is taking place; why the cement block cracked. It may be electrolytic corrosion of the iron, the formation of oxides which occupy a larger volume and so increase the size of the iron, and cause mechanical destruction by the irresistible force of the increase of volume which leads to cracking. It may also be electrolytic action resulting in the production of chemical compounds. We may think of chlorine attacking the concrete and softening it, or it may be still other actions; in short, the action of cement requires further investigation. In Mr. Hayden's paper also cement is mentioned; there the curious effect, where cement is not used by itself as in a concrete block, but added to soil, is that it increases the spontaneous corrosion of lead. That also may be a chemical action exerted by the cement on the soil. It also affects greatly the electrolytic action, different at 60 cycles from that at 25 cycles. In short, the whole phenomena resulting from stray currents on concrete structures may well be further investigated in view of the importance of concrete as structural material in the ground.

In regard to the protection, by negative feeders and the permissible potential drop against ground, the specifications of the German engineers are certainly very safe. If the potential difference between rail and ground in the return circuit is kept below one volt, there will be no trouble from electrolysis, because the pressure is below the dissociation voltage of water. This recommendation deserves to be classed with the recommendation of the American Water Works Association Committee of Engineers, in which they recommend the double-return trolley. The German recommendation is not quite as practicable, however, because one volt potential difference is impossible. I understand in England that the rail return drop has been restricted to seven volts. Those who have figured on negative feeders for any railway system know how handicapped the electrical railroads are with regard to this specification of seven volts return. To restrict it to one volt, if that is really the recommendation of the German engineers, would appear ridiculous. I do not think it can be done commercially, and I do not see any reason for it, since those metal structures which are most liable to be attacked are iron and they are always massive, and fairly well protect themselves. Lead requires special protection and can be protected by maintaining it negative against ground. I believe a more sensible specification would be not to limit the return drop at all, but to require that the underground metal structures which it is desirable to protect must be made negative and maintained negative against the rail, and then let the railroad company look out for their rails, which would be the only structure in which attack takes place. All the water and gas pipes should be connected to the negative terminal of the dynamo, and maintained negative. That is a complete protection for them.

J. L. R. Hayden (by letter): Confirming Mr. Kintner's statement under 3, I also found that it is necessary to have a duplicate cell for every test, to determine the chemical corrosion. I found, too, that special care must be taken to keep this control cell at the same temperature as the electrolytic cell. A water bath was used in all later tests for this purpose.

My experience does not quite agree with Mr. Kintner's 2, "that the edges of the plates were by far the most active part of the terminals." The plates were usually corroded fairly uniform all over, even on the back, and the edges not more than should be expected from the higher current density existing there.

Mr. Kintner's statement that the current densities assumed by me are very unlikely to exist in actual service conditions, I believe has been fully answered in the discussion by Dr. Steinmetz. Dr. Steinmetz shows that with a cable laid in a duct, and thus partly protected, the current density over the surface of the cable is distributed very unevenly; therefore, fairly high local current densities must be expected.

Regarding the voltage required to produce such current densities, I originally intended to record the voltage per cell also, but found that it was too low to be read accurately with the available voltmeters, in which the scale below 20 volts was not very reliable, and so I had to give it up. Usually from 6 to 8 cells were connected in series with a rheostat, in a 120-volt circuit, and herefrom it follows that the voltage per cell was well within the range of rail-return drop commonly found on American railways. In alternating-current railways at 25 cycles the resistance of the rail return is from 5 to 8 times greater than with direct current, due to unequal current distribution in the rail. The higher trolley voltage permits a higher voltage drop in the circuit, and in this case, even higher rail-return drops may be expected than with direct-current.

Philip Torchio (by letter): Will Mr. Corning please explain how it happened that with feeder districts of alternative signs of potential all the potential-drop readings obtained from water mains were shown on each and all curves all of one sign? One would expect to find negative and positive zones along the water mains traversing the territory, because if the current must practically all flow to the station by the way of trolley wires, this current must at certain points of the water main leave the mains as well as enter them at other points. Were the readings taken at random and the results accidental, or were the points of reading purposely selected?

John W. Corning (by letter): The points at which the readings of potential difference between pipe and rails were taken, were so chosen on account of accessibility to pipes at these points without excavation, and the length of line over which conditions were investigated was limited by the number of observers available at the time.

The feeder sections that were supplied with current from the negative pole of the generator to trolley were, as a rule, not the sections farthest from the power stations, but were midway between the inner and outer sections, so that the average condition of potential difference between pipe and rail would not reverse. Had feeder sections farthest from the power station been chosen it is probable that positive potentials on pipes would have been encountered.

A. M. Schoen (by letter): I am much interested in Mr. Knudson's conclusions, drawn from a thirty-day test with current flowing over pipes buried in concrete blocks which were in turn immersed in water. I have never made any detailed laboratory tests of this character, but some years ago while making a general survey in one of our larger cities, for the purpose of determining to what extent water pipes had suffered damage due to electrolytic corrosion, I had an excellent opportunity to note these points in the practical operation of a trolley system. The city was inland, hilly, and well drained, under which conditions the concrete road bed should naturally not be subjected to excessive moisture, the run-off leaving it ordinarily fairly dry. There were in operation in the city two independent overhead trolley systems with track return, one having an 18-in. concrete roadbed, the other having only cross-ties embedded in the soil. The track under which there was no concrete was in many places badly bonded, with resultant heavy leakage to water pipes; after leaving the water pipes much of this stray current found its way back over the better bonded tracks of the line having the concrete roadbed. In many places I found heavy damage done both to lead services and cast-iron mains under the tracks of the company using no concrete, while in no single instance, although a large number of excavations were made, did I find damaged even a lead service lying under the concrete. Instances were found where such corrosion had taken place just beyond the edges of the concrete, indicating that this was due to surface leakage. I attribute these results to the fact that the concrete being less porous than the earth, and, owing to good drainage, not continually soaked in water, formed a fairly good insulator and provided considerable protection for the pipes beneath it. With the concrete continually saturated with water, the results would naturally be different.

W. R. C. Corson (by letter): The facts brought out by the experiments recorded in the papers by Messrs. Hayden and Knudson will prove, I believe, valuable additions to engineering knowledge, and while some of the conclusions reached by the writers are probably assailable they serve a valuable purpose in giving direction to new thoughts on an old subject.

My interest has, however, been especially aroused by the paper presented by Mr. Rhodes, and I wish to pay the tribute of appreciation to his ingenious treatment of the subject. .The mathematical demonstration of the relative values in the several methods of return feeder distribution is one which will prove of great assistance in the study of the measures to be taken for relief from the effect of stray earth currents.

While I have not had time as yet to follow in detail the various steps through which the demonstration is carried, one conclusion, which seems to be proved and which was touched on but briefly during the discussion, appears worthy of emphasis by repetition; this is, that all methods of return-feeder distribution are more effective in reducing earth currents when the negative bus-bar at the power station is not grounded.

Now the negative feeders from the rail, if run underground in an uninsulated condition, form a more or less perfect ground for the negative bus-bar; and in proportion to the perfection of the ground so formed must reduce the efficiency of the relief from ground currents which they should afford. A corollary to the conclusions of Mr. Rhodes' paper would be therefore that, for efficient relief from earth currents return feeders must be insulated from earth.

It has usually been considered that the measures which a street railway company would naturally take in its own interest to reduce the amount of lost energy on its return system would be effective also in reducing the stray currents on other metallic structures in the streets. Mr. Rhodes' paper clearly shows that the different methods of feeder distribution would not be equally effective for both purposes. For instance, Case II of the paper represents perhaps the most economical method of reinforcing the conductivity of the rail for the purpose of reducing the drop in potential in the return circuit, but this method is shown to be least effective in diminishing earth currents. Again, a single feeder connecting the negative bus-bar to the middle of the track is very effective in reducing earth currents, and, as the effect is independent of the copper in the feeder, an installation of this method might be made without improving in any way the conductivity of the return circuit. The more one studies the question, the more forcible is the impression that the street railway's interest and that of other co-occupants of the streets are not equally served by any one measure of improvement.

This conflict of interest has been appreciated by all concerned for many years, although its existence has never been shown so clearly as by Mr. Rhodes' paper. Water and gas associations have received reports from committees appointed to investigate remedies for electrolytic troubles, and these reports have almost invariably demanded changed methods in the construction of street railways, changes which their economical operation prohibited. On the other hand, remedies have been suggested by the electrical interests such as the application of " drainage systems," the insertion of insulating joints in pipe lines etc., which while effective in certain cases, or in certain classes of systems, have been almost universally condemned as unfit by electrical engineers who have under their charge the care of long lines of lead jointed pipe.

It cannot but be a fact that all operating and most consulting engineers have to give the matter of electrolytic corrosion consideration from some point of view. In view of this it appears to me a proper time to suggest that the Institute has an especial opportunity of enlarging its field of usefulness by lending the weight of its authority to a set of recommendations governing the matter of relief from the effects of stray railway currents.

During the discussion, extracts were read from a report made to the American Gas Light Association, which contained the regulations governing the installation of return systems of conductors formulated by a body of German engineers. As I heard these regulations read they appeared for the most part of a reasonable nature, though certain of them were doubtless difficult of attainment. I did not understand, however, from the reading with what authority these engineers acted. If they represented a committee duly appointed by a national non-partisan association of engineers the regulations must have weight in their country and should doubtless prove the basis for "good practice" in installations of the nature covered by them.

In this country no association is so well qualified to take up this matter as our Institute; its membership is representative of the best talent in all fields of electrical engineering; it comprises the men who have been most responsible for the wonderful development of our street railway systems, and whose opinions on the requirements of such systems have become authoritative; it contains also those men who have devoted their abilities to a study of the damage which the railways have done or are doing to underground metallic structures; and men who have under their care the protection of lead-sheathed cables for the conveyance of electrical energy. These men have accumulated from extended experience and study a fund of data and general information on the subject in question, and a committee selected from such a membership would be particularly qualified to examine the whole subject and sift the good and practical from the bad or unwise methods of relief which are in vogue or have been advanced. The recommendations of such a committee modified or amended by a general discussion at an Institute meeting would unquestionably form an authoritative standard of practice which would not only tend to improved conditions of our buried structures, but would redound to the credit of our Institute and increase its prestige.

F. A. C. Perrine (by letter): The results of Mr. Knudson's experiments have been brushed aside by those who have discussed the paper on account, I believe, of a fear that there may be some truth in his statements that will put an additional burden on the street railways of the country. Unfortunately, particularly in reference to the Hamilton avenue bridge, Mr. Knudson has drawn some conclusions from his experiments which are probably not warranted by the facts.

I have no doubt but that a current sent through concrete will not only crack it, but will make it soft. In the case of the Hamilton avenue bridge, however, there is no evidence from the paper that the concrete was softened, and I understand from the engineer's report on the bridge that the cracking of the concrete was due to settling of the foundations. This is particularly emphasized by the fact that certain building foundations in the same neighborhood have also settled. But I agree with Mr. Knudson's conclusions that blocks of concrete will crack and are made soft by the passage of electric current, because I have had similar experience on quite a large scale with current passed through concrete. In some experiments made about a year ago to determine the efficiency of a large generator, the water rheostat was contained in a concrete basin. After a test lasting about twenty four hours the electrodes were taken from the concrete basin and the water pumped out for the purpose of making some changes in the machinery. Much to the surprise of all concerned, the concrete basin was found to be badly cracked, although during the time of passage of the current from one electrode to another a considerable quantity of water was kept flowing through the basin. The electrodes were three in number, each about four inches in diameter and set about two feet deep in the water, clearing the bottom of the basin by about six inches. The test stopped about 5 o'clock in the morning, and by 8 o'clock in the morning, after the water had been removed from the basin, the concrete was found to be hot and cracked badly, some of the pieces coming out being half as big as a man's body.

The concrete was found to be quite soft, so that it could be whittled like soapstone. This softening ran up along the side of the concrete basin. The damage seemed to have been done by currents passing through the concrete in their path from one electrode to another. I believed at the time, and still believe, that the damage was due to the heating of the concrete as the current passed through it, although this does not quite explain the softening of the concrete itself. In parts where the current must have passed in small amounts the damage to the character of the concrete seemed to be greater than would have resulted from boiling the concrete in water. As was stated earlier in the discussion, enough energy was passed through the concrete by Mr. Knudson to develop an appreciable amount of heat, and if this energy resulted in the dissociation of even a small amount of the water contained in the concrete, the cracks would naturally result. Furthermore, if this water in the concrete so dissociated were water of crystallization, not only would the concrete have been cracked, but it also would have been softened, as described.

I do not believe that there is real danger to buildings on account of this phenomenon, for the simple reason that the conditions for a current passing through concrete to a building frame are not generally present when the concrete is sufficiently wet to afford a ready path for the current; at the same time I have not the slightest doubt but that if the current passed through the concrete, the results described by Mr. Knudson would follow, although I question whether the results may properly be called results of electrolysis. I think that this subject is worthy of much more careful study than has been given it. I believe though that such a study will reassure, rather than discourage those owning concrete buildings.

A. A. Knudson (by letter): The tests shown in the paper are the first of the kind attempted by the writer, or by anyone else so far as the writer is aware, consequently the data are confined to what may be termed initial experiments. Had these tests been conducted over a much wider range as suggested, including an analysis of the many brands of cements, and the effect of currents upon each, it is doubtful if there would have been any practical difference in the results. Both the Portland and the Rosendale cements used in the concrete blocks were samples of brands commonly used in building all manner of structures.

The wrought-iron tubes were not turned or polished before being set in the concrete, but were well cleaned.

The weights in the tables are in avoirdupois ounces; all of them were made in the presence of the writer, and on a very delicate scale.

It has been claimed that no proof is presented that the splitting of the concrete blocks was due to electrolytic action. This question seems to have resolved itself into a difference of opinion as to what is proof. In the absence of other reasons for the splitting of the blocks, it may be said that blocks which had current flowing through them were split open, and the block which had no current showed no cracks of any kind, nor the first sign of corrosion upon the tube. The tests were repeated with practically the same results.

Dr. Steinmetz' remarks on this subject confirm my own view of the case. He said:

> It may be electrolytic corrosion of the iron, the formation of oxides which occupy a larger volume and so increase the size of the iron, and cause mechanical destruction by the irresistible force of the increase of the volume which leads to cracking; it may be also electrolytical action resulting in the production of chemical compounds.

Mr. Waterman said:

> Iron incased in concrete is like a battery electrode in a porous cup, so far as insulation is concerned.

Porous cups are not made to adhere to an electrode as is the case of iron in a concrete block. If this were the case they would doubtless crack open in a few hours. It is only where the tests show that a separation from the electrode was caused by the concrete splitting open that there is a similarity. Here probably is the cause of the increase of resistance after the cracks began to show; for as the cracks increased in size, and the concrete separated from the iron, the resistance increased.

In regard to the " restriction " of the flow of current due to a " highly resistant coating " upon the iron; it is pointed out in the paper that electrolytic action had progressed to the point that cracks appeared on the sixth day, and it was not until the ninth day that the rise in resistance really commenced, consequently there could have been no restriction of current flow until *after* considerable corrosion of the iron had taken place and the damage had been done. This test might have been terminated at the ninth or tenth day, so far as establishing the two points are concerned; namely, that concrete is no protection to iron against a current of electricity, and that concrete will be cracked and softened by such current. The voltage, however, was "remorselessly" raised to determine what the final effect would be on blocks in both fresh and salt water. Mr. Waterman said further:

> Just what a corroded water meter had to do with the subject is not clear.

It is distinctly stated in the paper that the two illustrations were placed there as an example of how currents do actually stray into buildings, or piers, and cause damage. Mr. Waterman also said:

> The corrosion of the meters was probably caused by *iron rust*.

As a matter of fact the meters were made of bronze, and the currents that caused their destruction were in each case traced from the car tracks.

Referring to Dr. Steinmetz' remarks:

> Fortunately iron is a material which is rather stable, and least attacked by electrolytic action. Even wrought iron is not attacked very badly, and steel much less, and cast iron is hardly attacked at all. The problem of protection against electrolysis is not the problem of protecting the rails or gas or water pipes. The underground metal structures which are suffering most are the underground lead cables, and there again it means the telephone cables.

This statement is quite surprising in view of the many instances of pipe destruction which are so generally well known. Even Mr. Corning, representing one of the finest electric railway systems in this country, has stated frankly that they were having a good deal of trouble from electrolysis in one part of their system on the large 48-inch cast-iron mains, and other mains of the Metropolitan Water Works, and they had installed a number of insulating joints in the attempt to prevent electrolytic action.

This is only one illustration from one city of damage by electrolysis to piping systems and other property. This information from Boston was furnished by railroad men. Their statements I can corroborate, for I have personally been on the ground and taken measurements in company with others.

Future experimenting with electric currents and steel in concrete will doubtless show further points of interest. The present paper giving the results of experiments is intended as a warning that concrete is no protection to iron or steel when electricity is passing through it.

H. W. Fisher:* Over ten years ago, when the first cases of electrolysis of the lead covering of cables were reported, I made a series of tests to determine the conditions both favoring and preventing electrolytic action on lead-covered cables. As anticipated, I found that only when the lead is positive to ground does injurious electrolysis take place. I also found that electrolysis is not prevented by the addition of 3% tin to the lead, nor by covering the lead with a weatherproof tape or braid saturated with insulating compound. In the latter case, electrolytic action is apt to be concentrated in spots, and thus eat through the lead cover more quickly. For the same reason, I also found that lead-covered cables laid in wooden boxes filled with pitch or bitumen deteriorate rapidly under electrolytic action. As a result of these tests, and others made on cables working under practical conditions, it was found that the amount of electrolytic action depends upon:

1. The proximity of cables to electric railroads.
2. The distance the cables parallel electric railroads.
3. The quality of the electric railroad construction work providing a path for the ground-return current.
4. Numerous other things, including the polarity of the ground return current, the conductivity of the soil, and the position of low soil or water resistance, either along the route of the cables or leading toward the power house, the proximity of the cables to water and gas pipes, the dry or damp condition of the ducts containing the cables, and the chemical constitution of the earth.

From the above data it is evident that the manufacturer of cables cannot guarantee them against electrolysis. He should, however, always be ready and anxious to prescribe such remedies as in his judgment will prevent electrolysis on cables which he has sold. With this end in view, at least one of the cable companies has printed literature dealing with the subject of electrolysis and giving preventive methods and remedies which have proved effective through repeated trials.

The introduction of the single-phase alternating-current railroad system with grounded return brings up the question of electrolysis with alternating currents, and I have been making some experiments to determine whether under any conditions the lead covers of cables may be destroyed by alternating-current. My experiments so far have not been very comprehensive, but I have found that under certain conditions destructive electrolytic action may occur with alternating currents operating at a frequency of 60 cycles.

The solution I employed for the electrolyte was water containing common salt and sal ammoniac, all of which may occur in and around duct systems. I found that with a current density of 0.1 ampere per square inch of lead there was no electrolytic action. With 3.04 ampere per square inch of surface, the amount of lead destroyed per ampere per hour per square inch was 0.004 grammes. With 11.8 ampere per square inch, the amount of lead destroyed per ampere-hour per square inch was 0.136 grammes. With 17.9 ampere per square inch, the amount of lead destroyed per ampere-hour per square inch was 0.237 grammes. In this last case, a large hole was eaten through the lead, and the surface exposed to electrolytic action was nearly one square inch. These tests were made without any attempt at great accuracy. The results show very plainly, however, that if the current density per square inch of surface is sufficiently great, destructive electrolytic action can take place with alternating currents.

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*Presented originally at a meeting of the Pittsburg Branch, December 12, 1905.

Thinking that the action might be due to the large amount of energy dissipated over a small area, I repeated the experiments with direct-current of slightly larger density per square inch, applying the negative side to the lead cover. No lead was destroyed. It may be possible that with other ingredients in the soil or ducts, the alternating-current action may be greater than that here given. While in many cases the current density per square inch of surface may not be sufficiently great to cause destructive action on the lead covers of cables, yet while there is a possibility of such action occurring, the cable companies cannot guarantee their cables against electrolysis from alternating currents.

The apparent remedy is to make the difference of potential between the lead cover and ground so small that the current density per square inch of surface is not sufficiently great to cause destructive action. This may be accomplished in different ways, depending on local conditions. With a frequency of 25 cycles, the alternating-current action would probably be greater than that shown by my tests.

R. A. L. Snyder: The name telephone cable is inseparably connected with the subject of electrolysis. No underground construction has suffered from the ravages of electrolytic corrosion quite so severely as the telephone cable. Our company's experience with this subtle destroyer has been a very sad one. In the early days of telephony we installed a large underground cable plant, and this plant, which cost us $150,000, was entirely destroyed by electrolysis. The plant was known as the "solid system" in distinction from our later plant, now in use, known as the "drawing-in-system."

The solid system was very carefully laid in order to prevent electrolysis. A wooden box was installed and the cables laid in the box on a layer of mineral pitch. The box was then filled with the pitch so as completely to surround the cables. A layer of pitch at least one inch thick separated the cables from the box on every side. Another precaution was taken, by attaching grounding plates to some of the cables at regular intervals; but with all this elaborate protection electrolysis destroyed the system.

At first very little trouble was experienced, for the reason that the electric roads did not become prevalent until about 1894. Before this time Pittsburg's longest street car line was a cable road. During 1896–7 our troubles increased rapidly, but thanks to the new drawing-in-system which we had started in 1893 we were able to replace the solid system very rapidly.

When one of these solid-system cables would show trouble, we had to locate it as closely as possible and then dig up the streets. This was a very expensive operation, especially when the trouble occurred in two places, which meant that we were obliged to open the street for a distance of three or four hundred feet. When the cable was uncovered, the sheathing would be found pitted in many places. Our first solid-system cables laid to the East End exchange had to be abandoned after operating only a few years.

So much for the solid system. The next problem after getting our cables installed in the new system was how to prevent them going the way of the old cables. The electric roads were increasing the size of their plants and the leakage of current was becoming greater. It was generally conceded that the best plan was to make the cables negative to earth as in the old system, as it was noticed that corrosion generally took place where the cables were positive to earth; but there were records showing that cables strongly negative to earth often generated chemicals which reacted to destroy the lead sheathing. This was especially true where the current was shut off during the night.

Some years ago a mass of slimy matter was taken from beneath the electric car rails on Boylston Street, Boston, and sent to the Massachusetts Institute of Technology to be examined, where it was found to consist mostly of sodium hydrate with particles of metallic sodium distributed through it. These particles of sodium burst into flame when thrown into water. Sodium chloride or common salt was used to melt the ice along the rails. This may have been turned into sodium when acted upon by currents flowing into the rail.

As the law at this time apparently furnished no protection to our property from the traction company's stray currents, we decided to go to the expense of running long bond wires to the negative poles of their generators, thus making the cables negative to earth. The result of this course has been very satisfactory compared with our former experience, but we have still had our troubles. At times our cables would carry so much current that they would arc to well-grounded conductors, burning holes through the cable sheathing. At Twenty-first Street and Spring alley the arcing was severe enough to set fire to a terminal pole and required the services of the fire department to extinguish the flames. In the neighborhood of Twentieth street, we had a number of cable terminals burnt where they passed through the pole pipes. This trouble became so bad that in several places we insulated the cable terminal from the pipes with rubber hose.

Several years ago, we had our cable system bonded to the traction company's negative return on Twentieth street with three No. 0 copper wires. These wires carried enough current to heat them to a temperature of 212° fahr. About this time we noticed a change in the electrolytic condition of our cables and upon investigation found that the wires were burned off a short distance from the manhole.

In some cases where our cables are positive to ground at distant points from the power houses, we have allowed them to eat away rather than to go the expense of running a bond wire. Our record of losses from electrolytic corrosion for the past few years is as follows:

1901—One case
1902—Two cases
1903—Two cases
1904—Two cases
1905—Seven cases.

Our troubles appear to be increasing, yet we have spent more money running bond wires during the past year than ever before, despite the fact that the traction company have electrically welded their rails. We have done everything known to the art to prevent electrolytic corrosion of our cables.

The drop in potential between our Grant office building and the cable sheathing at Twentieth street and Spring alley is often over twenty volts. Sometime ago we had some spare cable conductors grounded to the cable sheathing at Twentieth street and the current was used in our laboratory to run a small motor. There was enough current to light a 50-candle power 50-volt lamp to a bright red.

The anchors holding our aerial cables have also suffered from electrolytic corrosion. They have to be made negative to ground by running bond wires. This occurs in almost every town in our territory, and when an anchor breaks, the cables fall to the ground, causing a big repair bill.

For a long time the Ben Venue power house was run only for a few hours each day In this neighborhood we had much trouble from the continually changing conditions. I understand that the Pennsylvania Railroad had to replace their signal air-pipes in this neighborhood several times.

In conclusion, I would say that our present policy is to maintain all parts of the cable system free from electrical contact with underground steel and iron structures; to keep the parts well bonded together, and most of all to have them slightly negative to earth. I would advise all owners of underground metal construction to do likewise, until the traction company adopts some method of carrying return currents in its own conductors.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, New York, March 22, 1907.

Copyrig' 1907. By A. I. E. E.

MOTOR-GENERATORS *vs.* SYNCHRONOUS CONVERTERS

WITH SPECIAL REFERENCE TO OPERATION ON LONG-DISTANCE TRANSMISSION LINES

BY P. M. LINCOLN.

GENERAL

The particular problem to be considered in this discussion is the following: wanted, direct-current power of approximately constant voltage; for instance, for railways 500 to 700 volts, for an incandescent lighting system, 100 to 275 volts, for an electrolytic process, any direct-current voltage. Given as a source of power, a long-distance alternating-current transmission system, which may be either 25 or 60 cycles, may have a varying voltage at point of delivery, may have the variation occur either on account of the load taken by our particular station or independent thereof, and may have a somewhat variable frequency. Problem, what shall be used for making the desired transformation; synchronous converters? motor-generator sets with synchronous motors? or motor-generator sets with induction motors?

In this discussion a comparison will be made between these methods in regard to the following points, these points being placed, in the opinion of the writer, in the order of their relative importance.

1. Reliability.
2. Voltage regulation.
3. Corrective effect.
4. Efficiency.
5. Cost.
6. Parallel operation.
7. Starting.

These points will be taken up in the order named. As a matter of simplification, it will be assumed that the line voltage is too high for a revolving machine and must be transformed before utilizing.

1. Reliability.

In this connection, the term "reliability" is taken to mean simply freedom from accident, or, in other words, capability of performing normal functions continuously without interruption. Without this element of reliability, it is evident that no plan of transformation can be a success. To those charged with the responsibility of the operation of such a plant, there will be no question but that this feature deserves the first place.

As to reliability, it is evident that the synchronous converter has a very decided advantage in that there is only one machine to get out of order, whereas either of the others involves two. Further, we are forced to use a low voltage on the synchronous converter so that its insulation is normally called upon to stand a maximum of not more than 700 volts; whereas with the motor-generator sets other conditions may dictate a very much higher motor voltage, and, therefore, a lower factor of safety in insulation. Both the synchronous converter and the synchronous motor-generator set suffer the disadvantage that a momentary removal of the voltage from their terminals—a short-circuit on the transmission line for instance—will cause them to drop out of step and make it necessary to start them over again. In this respect the induction motor-generator has an advantage in that it will resume operation automatically after such a temporary cessation of incoming power.

As to "bucking," this is a fault that is more commonly attributed to synchronous converters than to direct-current generators, but the reason for it is that the converter is more widely used under conditions that will cause "bucking" than is the direct-current generator. The usual cause of "bucking" is the sudden occurrence and removal of heavy overloads; as, for instance, when a circuit-breaker blows. The ideal conditions for this occur on the average interurban road, where the sub-stations are relatively small compared with the maximum loads carried. A direct-current generator of the same size and exposed to the same conditions would probably give rise to about the same amount of "bucking." Exception is made in the case of the 60-cycle converter, which is admittedly somewhat more sensitive in this respect than the 25-cycle converter, chiefly on account of its necessarily short distance between brushes.

As a relative comparison of the reliability of the methods under consideration in railway work, the following is advanced as a personal opinion. The number given indicates the relative number of hours that the apparatus would be out of service within a given time on account of defects inherent in the apparatus.

25-cycle synchronous converter	10 hours.
Induction motor-generator	14 "
Synchronous motor-generator	17 "

2. VOLTAGE REGULATION

The term " voltage regulation " here will be confined to the changes that may take place in the direct-current voltage. The term embraces at least three distinct features:

a. Automatic change in voltage with change in load.

b. Ability to adjust the initial voltage.

c. Variations in direct-current voltage with variations in incoming line voltage and frequency.

Automatic Change in Voltage with Change in Load. In this respect all methods under discussion are equal. Rising or drooping characteristics of an adjustable value can be obtained with either the synchronous converter or the direct-current generator. The converter suffers the disadvantage that the power-factor of the current supplied must vary with varying loads, whereas with the motor-generator sets the direct-current voltage compounding adjustment is independent of the alternating-current circuit. This point will be further discussed under subsequent headings.

Ability to Adjust the Initial Voltage. It is in this respect that the synchronous converter suffers its greatest handicap. In the motor-generator sets the direct-current voltage is absolutely independent of the incoming alternating-current power. With the synchronous converter, on the other hand, the only way to adjust the direct-current voltage is to make a proportionate adjustment of its alternating-current voltage. There are several methods of accomplishing this end, which may properly be discussed under this heading.

One method is to insert a reactance in the alternating-current circuit of the converter. By changing the field strength of the converter, adjustments of the voltage applied to the collector rings can be obtained within limits, depending upon the amount of reactance and available field adjustment. The disadvantage of this scheme is that the alternating-current voltage is thereby made interdependent upon the power-factor of the incoming alternating-current power, and that the high-tension line voltage is dependent upon the direct-current voltage adjustment to an extent depending upon the relative reactance in transmission line and in the local converter circuit.

Another method is to use an alternating-current booster having the same number of poles as the converter and mounted upon the same shaft. This is approaching motor-generator conditions, except that the generator involved has to take care of only a small percentage of the output of the set under consideration, and the range of voltage adjustment instead of being from zero to the required amount remains between limits depending upon the relative output of converter and booster. This really makes a more logical arrangement so far as initial voltage adjustment is concerned than the motor-generator, since adjustment down to zero is never required in practice. The maximum range of adjustment ever required is the range of incoming voltage fluctuations plus the initial range required.

Still another method is the use of taps on the transformer stepping down to the converter, or of an induction or other type of alternating-current voltage regulator. These in general have the same effect as the booster just described. It is outside the range of this paper to discuss their relative merits. The addition of any of these means of voltage regulation makes the converter equal to the motor-generator set as far as ability to adjust initial voltage is concerned.

Variations in Direct-current Voltage with Variations in Incoming Line Voltage and Frequency. The difference between the converter and the motor-generator set in this respect consists in the fact that the converter responds only to changes in the incoming voltage and the motor-generator only to changes in the incoming frequency. This last statement may be modified slightly by recognizing that the slip of the induction motor depends upon the voltage, but the normal variations of voltage are so small that this feature can be safely neglected. For a given percentage change in incoming line voltage, there will be an equal percentage change in the direct-current converter voltage. For a given percentage change in incoming line frequency there will be a greater percentage change, nearly double, in the direct-current voltage of a motor-generator set. However, changes in incoming line voltage will under normal conditions be much greater and sharper than those in frequency, so that in this respect the converter will probably suffer by comparison with the motor-generator.

There are cases where, on account of voltage regulation, a straight synchronous converter would be absolutely unusable as, for instance, where a steady direct-current voltage for lighting is desired and the voltage of the alternating-current supply is varying due to causes other than the direct-current load under consideration.

The conditions which dictate the choice between converters and motor-generators with respect to direct-current voltage regulation are so variable that no attempt will be made to give any estimate of relative merits in numerical values.

3. Corrective Effect

By " corrective effect " is meant in general the results that may be obtained in respect to the voltage regulation of a transmission line by means of a change in the power-factor of the current taken. Only the synchronous motor and the synchronous converter need to be considered, since the power-factor of the induction motor is not adjustable.

It is desirable in any transmission line,

a. That the voltage shall remain as nearly constant as possible independent of the variation of load, and

b. That the voltage shall be capable of adjustment within limits at the will of the operator at any point.

So far as corrective effect is concerned, the synchronous motor has a distinct advantage over the synchronous converter in that the corrective effects may be obtained without involving the direct-current voltage. In the converter the corrective effect and the direct-current voltage are interdependent. On the other hand, when a converter is adjusted for a rising direct-current voltage characteristic, the tendency is to correct, in part at least, for the transmission-line drop caused by its own load. Thus it tends to fulfil condition (*a*) stated above. The synchronous motor can be made to fulfil condition (*a*) to the same extent by causing the direct-current generator current to flow through series coils on the motor field.

As to condition (*b*), both converter and motor field can be so adjusted by hand as to accomplish this end, but in the case of the converter not without making a simultaneous adjustment in the direct-current voltage. In order to secure the same independence of action with converter as with synchronous motor, it is necessary to have some means of adjusting the converter alternating-current voltage independent of simultaneous power-factor adjustment; as, for instance, the synchronous booster or voltage regulator described under the previous heading.

There is another point of view that should be presented before dropping this subject. A sub-station using the apparatus under discussion may or may not be under the control of the transmission-line operator. If it is, then its corrective effect can be used as transmission line conditions may dictate. If it is not under his control, the possession of corrective effect may not only be of no advantage, but also a positive menace to the proper voltage regulation of the line. If it is not under his control, he is probably better off with the induction motor-generator set, since it is neutral and possesses no power of changing line voltage at the caprice of an uncontrolled individual.

From the standpoint of corrective effect, therefore, the synchronous motor-generator has decidedly the advantage over the straight converter while the induction motor-generator is entirely neutral. No attempt will be made to give comparative numerical values since this depends, not only upon specific conditions, but also upon the point of view.

4. Efficiency

At the end of a transmission line power is usually sold by the kilowatt hour, or some other function that is proportional to it. The amount of the monthly bill will be proportional to the meter-reading, and the efficiency of the transformation therefore enters as a direct function in the cost of power. In this respect the converter has a decided advantage. It is a case of the losses in one machine as against those in two, and, moreover, the losses in the converter are somewhat less than in either element of the motor-generator set. The full-load efficiency of a converter of, say, 500 kw. capacity, may be put approximately at 95%, the synchronous motor-generator set, 89%, and the induction motor-generator set, 88%. The all-day efficiency will be considerably less than the above. As a reasonable estimate of the all-day efficiency under about 75%

load, the following is submitted. In submitting these the writer has in mind units of 500 kw. capacity or thereabouts:

25-cycle synchronous converter	93%
Synchronous motor-generator	85%
Induction motor-generator	84%

The following calculation based on the above is somewhat surprising. Assume a station using a 500-kw. unit an average of 18 hr. per day at 75% average load. Assuming power to cost one cent per kilowatt-hour, the saving in power bill per year of converter over motor-generator is $2100.00. Capitalized at 6%, this represents $35,000.00. In other words, one could afford to pay $70.00 per kilowatt more for converters than for motor-generators.

5. COST

In regard to cost, the synchronous converter has an immense advantage. Here again, as in efficiency, it is the cost of one machine against two; and the cost of the converter is not far different from that of each machine that goes to make up the motor-generator. An approximate idea of relative cost is given in the following:

Synchronous converter	60%
Synchronous motor-generator	100%
Induction motor-generator	100%

6. PARALLEL OPERATION

The two points to consider in parallel operation are:

a. Proper division of direct-current load between units.

b. Proper operation so far as alternating-current ends are concerned, such as freedom from "hunting," etc.

As to division of direct-current load, there is no question either on direct-current generator or converters. In fact, it is perfectly possible by proper adjustment to operate converters and motor-generator sets of both kinds all in multiple.

As to operation on the alternating-current ends, the induction motor-generator is the least liable to trouble, since "hunting" or "pumping" cannot take place on that type of machine. The synchronous motor and converter are on a par in regard to hunting. However, with the modern construction of synchronous machines, including as they do heavy dampers, there is so little probability of hunting that it may be entirely neglected. The only places in which hunting is apt to occur are in cases where antiquated generators are used and where the ohmic line drop is very high. Neither of these is apt to occur in practice.

7. Starting

In starting the desirable features are:

c. Minimum draught of current from line of starting from alternating-current end.

b. Ease of synchronizing.

a. It is difficult to make any of the apparatus under discussion of such design that it will start readily from the alternating-current end. Good running characteristics invariably mean poor starting characteristics. The inherent starting characteristics of the synchronous motor and converter are bad on account of the large air-gap. The converter has the advantage of only having one-half the mass of the motor-generator to start. The induction motor-generator set has the advantage of better starting characteristics, but it suffers in comparison with the converter in having double the mass. If started from the collector rings, the converter suffers by liability of damage to commutator by burning and sparking. A draught of full-load current or less from the line is usually sufficient for starting any of the sets.

If it is essential to keep down starting current, a starting motor can be employed. In this case the converter again has the advantage of one half the mass as well as one-half the losses of the motor-generator set. The same advantage applies to starting from the direct-current end, but is partly off set in the converter by the shunting effect of the static transformers, if these be connected.

b. In synchronizing, the induction motor has a great advantage in not requiring synchronizing at all. As between the converter and the synchronous motor, the converter suffers the disadvantage of having a commutator connected to the winding being synchronized, and, therefore, liable to injury by careless manipulation.

Altogether, there is not much choice in the starting qualities of the three methods, but what there is would cause them to be arranged in the following order:

1. Induction motor-generator.
2. Synchronous converter.
3. Synchronous motor-generator.

SUMMARY

On three of the preceding seven counts; namely, 1, 4, and 5, the converter has a distinct advantage.

On one more, 6, all methods are taken as being on a par.

On the remaining three, 2, 3, and 7, one of the other methods has the advantage. In one of these, 7, the disadvantage of the converter is not marked. The converter's disadvantage on the other two largely disappears with the addition of a means of voltage regulation.

This analysis, therefore, would seem to indicate that there are but few cases where the motor-generator should be used in preference to the synchronous converter.

DISCUSSION ON "MOTOR-GENERATORS *vs.* SYNCHRONOUS CONVERTERS, WITH SPECIAL REFERENCE TO OPERATION ON LONG-DISTANCE TRANSMISSION LINES." AT NEW YORK, MARCH 22, 1907

A. H. Armstrong: In regard to the use of motor-generators or synchronous converters, the question seems to me to be one of voltage regulation. The requirements of a railway system fed from a general transmission system are best met as to first cost and efficiency of operation by the adoption of the synchronous converter, and its almost universal use in railway installations would seem to leave no room for argument. The requirements of a direct-current lighting load can also be best met by the adoption of the synchronous converter, provided the distribution system is used for lighting only. Where, however, the distribution system supplies a mixed lighting and railway load (or any other load occasioning extreme fluctuations) the lighting system should be fed through motor-generator sets in order to smooth out the effect of unavoidable voltage fluctuations. Taking this broad view of the situation, there is a well-defined field for both synchronous converters and motor-generator sets, the question of voltage regulation determining the choice of either type of apparatus.

W. L. Waters: The reliability of operation of these different classes of machines is mainly a question of the care they get in operation. The induction motor is the only one that presents any disadvantages as regards actual construction of the machines. The small clearance between the rotor and stator with which these machines operate makes them more liable to mechanical troubles, and the small slots which it is necessary to use in the stator make it more difficult to make a satisfactory job of a high-voltage winding.

On the question of flashing over, the synchronous converter is decidedly more sensitive than the direct-current generator. The fact that the alternating- and direct-current sides of the converter are so intimately connected, combined with the fact that there is no armature reaction in such a machine to limit the current on short-circuit, make it peculiarly sensitive to sudden fluctuations on one of the circuits. For carrying overloads, the converter is superior to the direct-current generator, but it will not stand short-circuits or violent fluctuations on either circuit so well.

If voltage regulation is of importance, it is practically impossible to use a synchronous converter. With a synchronous converter we are dependent for voltage regulation upon the voltage supplied on the alternating-current side. If the synchronous converter is the only machine on that particular line, then by introducing artificial self-induction into the line and putting a series winding on the magnets of the converter, we can compound the line and so to a certain extent make the voltage change automatically with the load; but this means varying the power-factor of the converter and of the system within quite wide limits, and also that this change of voltage on the line affects all other apparatus on that line. The only other way of adjusting the voltage delivered by a converter is by introducing some sort of an alternating- or direct-current voltage regulator or booster, which of course means extra complication, extra cost, and lower efficiency.

As regards corrective effect for power-factor, this can practically be obtained only by the use of a synchronous motor-generator. On account of its low power-factor, an induction motor is very undesirable at the end of a transmission line and would not usually be considered unless it were possible to correct this low power-factor by introducing a leading current into the line. This can only be done practically by means of a synchronous motor. A synchronous converter can be made to introduce a leading current into the line, but this would mean varying the direct-current voltage and power-factor of the machine.

In using a motor-generator at the end of a long transmission line, it would undoubtedly be necessary to employ transformers for lowering the voltage before delivering it to the synchronous motor. In this case the synchronous converter has a considerable advantage in regard to efficiency. The value of this difference in efficiency has to be decided in each case by the cost of producing the extra kilowatt-hours. In a steam plant where the cost of fuel is high, this may be quite important, but as most long-distance transmission lines are operated from water power the cost of producing the extra kilowatt-hours is quite small. Practically, the only bad effect of the lower efficiency is that it reduces the capacity of the power-house machinery somewhat.

The relative cost depends a good deal on the particular machine that we are considering. If we consider a 1500-kw., 275-volt, 25-cycle machine, the synchronous converter would run at about 187 rev. per min., as this machine could not very well be built with less than 16 poles, while the motor-generator set could, by using an interpolar design, be built to operate at a speed of 300 rev. per min. or even higher. In this case there would be practically no difference between the cost of a synchronous converter and that of a synchronous motor-generator set. The introduction of interpolar designs in large direct-current work makes the direct-current generator the equal, if not the superior, of the synchronous converter, at the same time it is not subject to the limitation that the speed is dependent upon the number of poles on account of the frequency.

Referring to the question of starting. The induction motor-generator set is undoubtedly the simplest. The synchronous motor-generator only differs from the induction motor-generator in that it is necessary to close the exciting circuit and to synchronize the machine after it is up to speed. The starting of a synchronous converter is considerably more complicated than that of a motor-generator. If the converter is compound wound, we have to short-circuit the series coils when starting from the direct-current side. Then we have to synchronize carefully, and an error in throwing the machine on the line is much more liable to do damage or cause a flash-over than in the case of a motor-generator, as there is nothing to limit the short-circuit currents that would flow. If we start from the alternating-current side, we have to see that the polarity and voltage are correct before we throw them on the direct-current line. Throwing a synchronous converter on the line is a more sensitive operation and one which is more liable to cause damage than the same operation with the motor-generator, and in consequence the operator must be proportionately more skilful.

Speaking generally from the operating standpoint, a motor-generator is preferable to a synchronous converter in almost every respect, except as to efficiency and cost. And even as to cost a motor-generator is cheaper for low voltages and larger outputs, especially if the voltage on the transmission line is not over 15,000 volts, when the synchronous motor could be wound to take the high voltage direct. When comparatively cheap and medium-size units are wanted, and under conditions where close voltage regulation is unimportant, synchronous converters would be used; when large-size units are desired and when the voltage regulation and general flexibility are important, motor-generators would be preferable. In situations where the machines are to run with practically no attention, probably induction motor generators would be perferable to synchronous motor-generators. But the fact that synchronous motors can be used to control the power-factor of the line is of such importance in long transmission lines that the engineer should adopt them wherever possible.

H. G. Stott: In regard to Mr. Lincoln's comparison of the characteristics of motor-generator sets and synchronous converters, my own experience confirms his statements. During the initial period of the operation of a water-power plant, the voltage regulation was fairly good, but the speed regulation was poor; with these conditions, the synchronous converter gave the best results, but later, when the number of generators in service had been increased and the line regulation had become poorer, owing to the increased load, we had to resort to motor-generator sets, in order to obtain regulation suitable for lighting.

In reference to the various methods of starting, it is desirable to remember that any method involving starting from the alternating-current side means a rush of current equal at least to full-load current, at a power-factor of less than 25%; whilst starting from a motor coupled to the shaft, or from the direct-current side involves the use of only 4% of the full-load current, at unity power-factor. The first, or purely alternating-current method, may cause a serious disturbance in the circuit, resulting in hunting, and violent surges of current and voltage if the circuit is in a condition approximating resonance.

With the induction motor-generator set, however, another condition obtains, as when we start it from a separate motor or from the direct-current end, and after bringing it up to full, no-load speed and throwing it on the line, there may be a rush of magnetizing current equal to more than 10 times full-load current. This is the same phenomenon as observed when throwing current into transformers, the value of the momentary current depending upon the point of the cycle at which contact is made, with relation to the point of the cycle at which the current was previously broken. With large induction motors, it is therefore necessary to introduce resistance or inductance at the moment of closing the circuit, but this resistance may be cut out again after a few seconds, as this enormous magnetizing current lasts only for a few alternations.

Ralph D. Mershon: I cannot quite agree with Mr. Lincoln as to the relative reliability of motor-generator sets and synchronous converters. I have been closely associated with one installation where power is supplied in part by 60-cycle induction motor-generator sets and in part by 30-cycle converters. While there has been very little trouble due to either type of machine, such trouble as there has been, is more chargeable to the converters than to the motor-generator sets, although there are a good many more of the latter than of the former. This is in spite of the small air-gaps of the motors. We have not had in the installation I refer to any trouble such as Mr. Stott speaks of in regard to throwing the induction motors on the line though this may be partly due to the higher frequency. I am quite sure that the company supplying the power would make it known if there had been much disturbance when the motor-generator sets were thrown on the line.

It seems to me that in Mr. Lincoln's introduction, and the discussion of it, there has not been enough stress put upon the fact that operation of the motor-generator set is largely independent of the line voltage which it receives, and that therefore it is very well adapted to operation on very long transmission lines, where the full-load voltage at the two ends of the line will differ widely. In some instances this difference of voltage and the consequent variation between no load and full load of the voltage of the converters at the ends of the transmission line will not be a serious drawback. In other cases it may constitute a serious objection, and in any case it certainly is a very attractive condition of affairs to have along the transmission line motor-generator sets whose operation will not be materially affected by considerable variations of transmission line voltage this will apply to both induction motor-generator sets and synchronous motor-generator sets; but it is also a great advantage at times to have the equalizing effects which may be obtained from a separately excited synchronous motor in assisting to maintain an approximately constant voltage on the transmission line. In general, in any engineering problem we must adopt the apparatus to the conditions to be met. Undoubtedly, where the converters can be used without serious disadvantage, there is a very great deal in their favor on the score of efficiency, and also on the score of first cost. I believe with Mr. Waters, however, that if some work were done in the matter of raising the speed of motor-generator sets the difference in cost would largely disappear.

Charles W. Stone: It is simpler to insulate a generator coil than it is a high-voltage transformer coil, for the following reasons: The generator coil is usually small, and when insulated is usually quite stiff and rugged; whereas the transformer coil being comparatively thin and quite wide and flat, making it very difficult to get an insulation which will be continuous and will not be subject to movement and consequent deterioration.

When low-voltage taps on the transformers are used, the starting of converters is much simpler than the starting of a motor-generator set. I have seen machines as large as 1500 kw. started from the alternating-current side and brought up to full speed within 40 seconds. This means, of course, a considerable rush of current, but shows that it is possible in cases of emergency to start a converter quickly; in fact, much more quickly than a motor-generator set of similar capacity.

In regard to the number of hours that the different classes of machines would be out of service, due to defects inherent in the apparatus itself, I do not agree with the order given in the third page of the paper. I should place the synchronous converter first, next the synchronous motor-generator set, and next the induction motor set. I am basing the above conclusions upon a careful study of complaints which have been brought to my attention, and which clearly indicate that there has been more trouble with the induction motor sets than with the synchronous motor sets.

In regard to the relative efficiencies of the different combinations, I would say that the author's table applies only to the 25-cycle synchronous converters, as the efficiencies of the 60-cycle motor-generator set will approach very closely those of the converter sets. The 60-cycle converter will probably cost as much if not more than a motor-generator set.

Mr. Lincoln says that induction motor-generator sets do not hunt. I cannot quite agree with this, as I have seen induction motor-generator sets hunt considerably under certain line conditions. It is possible to make them hunt under test.

The author says, that with the motor-generator set there are two machines to look after. That disadvantage is, I think, somewhat offset by the fact that the converter has very large collector rings and brushes and heavy copper connections. I anticipate as much trouble with the collector rings and brushes as with the synchronous motor end of a motor-generator set.

Mr. Lincoln also says that the induction-motor end of a motor-generator set has an entirely neutral effect on the line. I do not think that this is quite true; it has a very serious effect on the line, and that is in lowering the power-factor.

Charles F. Scott: Mr. Lincoln's paper is excellent in that it gives a general survey of conditons pertaining to a given class of service. Very often engineers are apt to present a certain class of apparatus as the only one which is suitable; one man, for example, advocates the induction motor; another, the synchronous motor, and still another cares for nothing with alternating current in—it each maintaining that his class of apparatus is the one for all cases. A paper of this kind shows the wide field of conditions which exist, and shows that each of several kinds of apparatus may have its own proper place under certain conditions.

The general conditions applying to the three classes of apparatus considered have been presented; the second step in the problem should be to determine the results of experience. What has been the concrete experience with each these different classes of apparatus? Mr. Lincoln has given his opinion in a certain order of preference of the different classes of apparatus, and some others have expressed opinions reversing his order. If we could get from the operators of the several classes of apparatus their different experiences, it would give us some excellent data. For example, when we are told by one gentleman that induction motor-generator sets give greater cause for complaint than other classes, it raises the question: If this is the case, why is it? The simplest kind of apparatus is the direct-current generator on the one hand and the induction motor on the other, but if, however, these are not found in practice to give the best results, it will be interesting to know more in particular just why.

Philip Torchio: I am willing to endorse all of Mr. Lincoln's conclusions as far as applied to existing moderately-high-tension voltage systems operating relatively short lines. I do not think it justifiable, however, by actual experience to apply the same conclusions to the specific conditions of the paper, having special reference to long-distance transmission lines. In this case experience with synchronous converters is very limited, and the author has pointed out two serious drawbacks which, in my opinion, would in most cases preclude the use of converters. One of these drawbacks is the fact that converters fall out of step when the ohmic line drop exceeds a certain percentage, which is generally limited to ten per cent., and it seems to me that any momentary heavy short-circuit at the end of a long transmission line would be a menace to the continuous operation of the converters. The other drawback is due to the independence between line-voltage fluctuations and direct-current voltage regulation. I am certain that with most of the lighting systems this fluctuation would prohibit the use of converters. I would even go a step further and state that with 25-cycle transmission lines, frequency-changers of from 25 to 60 cycles should be installed; not only for the reason of the higher frequency required for good incandescent lighting, but also on account of regulation.

The question of variation of frequency can be remedied at the generating station, but it would be almost impossible to expect the generating station to regulate the distributing voltage with fluctuating loads on the line.

P. M. Lincoln: Mr. Waters says that the synchronous converters would compound the whole line when compounding themselves. This is true to a certain extent only; it is usual in operating converters to place in each individual converter circuit a rather high reactance which has largely the effect of making only the converter compound. Such reactance has the further effect of answering the objection to the large amount of current that a converter would take when short-circuited; the reactance has the effect not only of making the converter compound, but also of limiting the current on the short-circuits. Mr. Waters further says that efficiency is not a very important point, because water power doesn't cost anything. This is an easily answered argument. If power is being paid for, the power wasted has to be paid for as well as that used, and this applies whether the power is generated or bought.

As to the contention that converter speeds are necessarily lower than those of motor-generator sets, I take exception to that statement. I dont see why converter speeds cannot be made as high as motor-generator speeds.

To the statement made in my paper that the induction motor is neutral in its reaction on the line, objection is made that the induction motor is not neutral—that it is highly inductive. Closer reference to my langage will show that my point is that the induction motor is neutral so far as its capability of adjustment is concerned; it takes one position and stays there.

Mr Torchio intimated that trouble might be expected from converters where the ohmic line drop was ten per cent. or more. I should like to raise that limit a little, to something nearer twenty per cent., I know of cases where converters have been successfully operated when the ohmic line-drop was considerably more than ten per cent. Also tests have been carried out which indicate that the converters can, under favorable conditons, be operated with an ohmic line-drop of twenty per cent., and possibly more.

B. A. Behrend: I want to ask Mr Lincoln in regard to the subject of his paper why he has not included a 60-cycle converter in the list of machines out of service for a certain number of hours. How many hours would a 60-cycle, 600-volt synchronous converter be out of service?

P. M. Lincoln: I think it would depend entirely upon the time at which the converter was designed. The design of 60-cycle converters has improved wonderfully during the last decade. If it were designed in the last three or four years, I should put it somewhere between the 25-cycle converter and the induction motor-generator—say 12 hours.

B. A. Behrend: There is another point on which I wish to ask Mr. Lincoln. I quote from his paper:

> However, with the modern construction of synchronous machines, including as they do heavy dampers, there is so little probability of hunting that it may be entirely neglected. The only places in which hunting is apt to occur are in cases where antiquated generators are used and where the ohmic line-drop is very high. Neither of these is apt to occur in practice

I am afraid that this statement is not altogether true. I am quite willing to state that hunting does not occur very often, but it does occur in some cases, and in such cases it is often very obdurate and it is difficult to account for the causes in a satisfactory manner. I should like to know why the ohmic drop has such considerable effect; it, of course, limits the overload capacity of the synchronous machine; it changes the characteristic frequency of the oscillation; and if there exist in the system somewhere forced perturbations of a given frequency, then there may be a resonance effect produced by an increase in line resistance. But even this does not explain thoroughly why line resistance is made responsible for hunting. Mr. Lincoln's statement that hunting in modern synchronous machines can be neglected seems to me somewhat broad, although Mr. Lincoln allows himself a loophole by stating that this is the case only with modern generators and converters of a recent style with heavy dampers. I should like to ask Mr. Lincoln why he considers line resistance responsible for hunting?

P. M. Lincoln: Hunting always means that the rotor of the machine that is hunting is departing from its true mean path—periodically ahead of and behind that path. The magnetic field which flows from the pole into the armature is shifting constantly from one side to the other of the pole. The way to prevent that is simply to put grid dampers upon the iron of the pole, and in that case if there is any tendency for the flux to shift across the pole face, large currents are set up in these dampers which oppose the shifting of the magnetic lines.

The application of grid dampers, judging from the experience has been a complete cure for hunting—the exceptions being accounted for on high ohmic drops.

B. A. Behrend: What is the effect of the ohmic drop in regard to hunting?

P. M. Lincoln: I am unable to give you an exposition of the reasons at this time. We have made experiments to determine the limits of ohmic resistance and have found that under favorable conditions the grid damper would prevent hunting with an ohmic drop as high as 20%. The final limit may be even higher than this.

J. R. C. Armstrong (by letter: I am in full accord with the conclusion stated in the last paragraph of the paper, to the effect that, " there are but few cases where the motor-generator should be used in preference to the synchronous converter".

I understand that the object of this paper is to determine which of the three devices—synchronous converters, motor-generator sets with synchronous motors, or motor-generator sets with induction motors—is the best for transforming alternating current into direct current, and, at the same time, maintaining a constant voltage on the direct-current bus-bars.

It seems to me that the items " Parallel operation " and " Starting " should precede " Efficiency " and " Cost", as these factors are vital to the successful operation of a plant.

Reliability. or continuity of operation is I think the most important condition to obtain, especially at times when the greatest demand is made upon the respective pieces of apparatus.

I believe that undue prominence and stress has been laid on so called " bucking " or arcing over on the synchronous converters. It is true that this occasionally happens, but in a well-designed converter the percentage of trouble in a station due to this cause is very small. When bucking does occur, very little damage results to the converter, due to the highly developed protective switchboard apparatus installed on the alternating-current and direct-current sides of the converter circuits. It is very seldom that a short-circuit on transmission lines, either on alternating-current or direct-current sides, causes the converter to arc over, due to the fact that the overload device on the breakers will operate and thus clear the station bus-bars. A great deal of the trouble experienced in the operation of converters is due to the fact that the negative side of the circuit has been grounded and no attention has been paid to insulating the machine from the ground. It is readily seen that since there is a short distance between the commutator bars and the frame of the machine, there is only this short distance between the commutator bars and the ground when the frame of the machine is thoroughly grounded. Bucking due to this cause can be very easily obviated by insulating the machine from the ground; in other words, installing it on insulating material that will not allow an appreciable current to pass from the commutator bars to the frame.

In my opinion, the time assumed for the synchronous converter being out of service is too high. I think that this figure (10 hours) can be materially reduced.

Voltage regulation. With regard to the statement in the paper on " Variations in direct-current voltage with variations in incoming line voltage and frequency." I do not believe that such great variations may be expected. Should large variations occur, it would be on an exclusively railway system where the fluctuations in direct-current voltage would not be a serious matter; whereas, where a steady direct-current voltage is required, as, for instance, in a lighting system, the period of fluctuations would be quite long, in fact long enough to allow the operator in the generating station to change the field strength on the generator in order to hold the voltage more or less constant. This, I believe, would likewise apply to most systems composed of a combined lighting and railway load. Therefore, I believe that the synchronous converter compares favorably with the motor-generator set and not unfavorably, as mentioned in the paper, for operation under ordinary conditions.

Parallel operation. In the present state of the art of designing synchronous motors and converters, I agree with the writer that "The synchronous motor and converter are on a par in regard to hunting". The question of hunting on the last two mentioned machines may be neglected.

Starting. It might be mentioned in connection with the amount of current that these respective kinds of apparatus take from the line, that the induction-motor set is very bad in this respect. For in the case when a heavy draught of current is taken from the line, thereby setting up line disturbances, the induction motor-generator set is very conducive to this condition.

When new and in good condition, the motor will require a considerable interval of time to bring the machine being started to synchronous speed before switching it on the line. This operation will sometimes take as much as five minutes. A much simpler and quicker method of starting, and one which does not draw a large amount of current from the line, is that of starting from the direct-current bus-bars of the station. This can be accomplished very simply, and no time is lost in waiting to get the machine at the exact frequency of the line. It can be done by sectionalizing the field and connecting the field leads to a multiple-point switch that will introduce into the field circuit when opened a large amount of resistance, thereby largely reducing the normal current flowing in the field, and at the same time causing a very slight increase in voltage on the field windings. With this switch, a tripping device for the direct-current breaker can be operated and connected in such a way that the direct-current breaker through which the machine is receiving its power can be tripped before the high resistance is thrown into the field circuit. A second contact can be attached to this switch for closing the alternating-current circuit on the converter; this operation following immediately the introducing of the high resistance into the field as above mentioned. It will be seen that in the one operation above outlined, three things are accomplished; namely, the cutting off of the starting current, the introducing of a large resistance into the field circuit; and the closing of the oil switch—all three operations following one another in the order named. Then the machine cuts in on the alternating-current side when the armature is practically "floating", due to its own momentum, at approximately synchronous speed, and cut off from the direct-current source of power.

After the above operation has been carried out, the high resistance is cut out of the field circuit by closing the multiple-point switch and the machine is then ready for service. It will be seen that there can be very little strain or jar thrown on the armature in starting a machine by the above method. Units of large size can be started by this method by the ordinary operator in one minute or less. Therefore, I cannot see why the more expensive methods as proposed in this paper for starting machines of the above mentioned type should be employed, except perhaps where one of the above methods might be installed for starting one machine in case of emergency when no direct-current power was obtainable in the station.

The above method of starting machines from the direct-current bus-bars is now employed in quite a number of sub-stations in New York where converters are installed. It has been giving entire satisfaction.

In regard to cost of apparatus for starting, it might be mentioned that the cost of installing a switch as described above is only nominal, compared with the cost of other types of starting apparatus.

The advantages of the synchronous converter over the motor-generator are very marked, especially with respect to reliability, which I believe to be the predominating feature. Further, there is a wider range of application of the synchronous converter than there is of the motor-generator.

A. H. Babcock (by letter): A single qualifying clause should be added to the author's conclusions; that is, provided that the line frequency is not greater than 25 cycles. Experience on long lines in the West, especially where an extensive distribution system is operated, shows plainly that synchronous converters should be barred entirely where frequencies as high as 60 cycles are used.

For railway work, especially where the generating station distribution is under one control, and the frequency can be made 25 cycles or less, synchronous converters are to be preferred.

For 1200-volt lines, the indications are that ordinary 600-volt generating apparatus operated in series will give satisfactory results, although there is no experience in this country, at the present time, on which to base a positive opinion.

F. G. Baum (by letter): This paper assumes that 60-cycle converters are as satisfactory in operation as motor-generators. In any event, the author seems to have had in mind a 25-cycle system.

Assume for example that a given district is to be supplied by direct current at several points, also 60-cycle, 2300 to 10,000 volts for light and power circuits from a 60-cycle power system. The substations feeding the light and power circuits are also to be used for the conversion from alternating to direct current.

In this case, to the cost of the converter there must be added that of a bank of transformers and regulators to supply it; add also the losses of the transformers. This would bring the cost of the converters and transformers to about 80% of that of the motor-generator, and reduce the efficiency of the converter to about 90%.

The extra floor space for the transformers must also be considered. Also the great advantage the motor-generator set has in regulation on the alternating-current side, as well as on the direct-current side. These advantages are of great importance, and, considered in the light of present experience with 60-cycle converters, the motor-generator would generally be selected for the conditions here assumed. The conditions here assumed are those generally prevailing, except where there is a special system for the railroad power.

Ernest J. Berg (by letter): My judgment is that the synchronous converter is likely to play even a more prominent part in the future than at the present time. I quite agree with Mr. Lincoln in regard to the reliability of the converter as compared with the other types.

Regarding the voltage regulation. I do not think it serious that the power-factor is affected by automatic voltage regulation. Considerable control can be had with but slight change.

In most long-distance transmission lines, considerable lagging current is not objectionable at light loads, because the charging current is larger than the lagging current, due to the induction load. In its control of voltage, the converter can be adjusted to take considerable lagging current at no load and practically none at full load. Therefore, the converter might advantageously be operated with such automatic control. In low-voltage transmissions, which however are outside of the scope of this paper, there would be some objections on this score.

I quite agree with the conclusions given under the heading "Corrective effect" and also under the heading "Efficiency." The question of cost I can hardly pass upon, but I recollect some cases in which the cost of the synchronous converter with its transformer was practically the same as that of high-speed induction or synchronous motor-generators.

Regarding parallel operation. My experience leads me to believe that a properly designed synchronous converter operating on a 25-cycle system can be made quite as stable as any synchronous motor-generator, even if the latter is equipped with various kinds of anti-hunting devices.

Regarding the heading "Starting". I consider that the three systems are practically on a par. Induction motor-generators will take about as much current as any of the others, if special starting devices are omitted.

My conclusions, therefore, agree with those of Mr. Lincoln, that in most cases the synchronous converter offers advantages over the other two kinds of machine. I consider that in high-potential transmissions where there is usually a leading wattless current, the induction motor is preferable to the synchronous motor in every case.

R. G. Black (by letter): This paper refers to matters that interest not only the electrical engineer, but the operating man the capitalist, and the customer. In my opinion it is hard to consider the various heads under which the paper is discussed for both railroad work and lighting and power work, as what might be entirely satisfactory for railroad work might be otherwise for lighting and power work. From the point of reliability I would say that our experience leads us to differ with the writer of the paper as regards the motor-generator set, as generally designed, resuming operation automatically after temporary cessation of power supply; for if the speed should drop below 50 per cent. it is very doubtful, with the load of incandescent lights, direct-current motors, etc., if the induction motor would resume speed without drawing sufficient current to trip the automatic alternating-current line circuit-breakers. However, with a specially designed coil-wound induction motor, so arranged either by means of a centrifugal device or an electrical device automatically to put resistance in the rotor circuit, should the speed drop, say, 25 per cent. below normal, it is quite possible to arrange a motor-generator station so that the induction motors will automatically resume operation notwithstanding the direct-current load remains on. With motors arranged as above, I should be much inclined to place the induction motor-generator set first on the list, with the 25-cycle synchronous converter second, with about the same number of hours as shown.

Speaking generally, on every point except cost I should be inclined to favor the specially arranged, coil-wound induction motor as being the most reliable, easiest operated, and least objectionable of the three classes of machines discussed. In the matter of cost there is no doubt but that the synchronous converter has the advantage, particularly if its overload capacity is taken into consideration, but unless the operating company controls the transmission company, or has an agreement with them whereby the variation in voltage is not excessive, the cost of a large enough induction regulator brings the cost of the converter, with transformers and regulator, very nearly equal to that of a motor-generator set for a given kilowatt capacity. If the induction motor sub-station is close enough to a terminal station so as not to make transformers necessary, it might in some instances be cheaper than the synchronous converter set.

At one of the plants with which I have been affiliated, which is connected to a long-distance transmission system, arrangements are being made to purchase five 1500-h.p. induction motor-generator sets for lighting and power work in preference to synchronous converter sets or synchronous motor-generator sets, the idea being that they will be much more reliable, easier to operate, and more satisfactory in every way than either of the other types of machine.

Edward P. Burch (by letter): The writer's experience is that 60-cycle converters are not reliable. They are therefore unsatisfactory for 600-volt electric railway service. He would recommend the purchase of the higher price and lower efficiency synchronous motor-generators in place of 60-cycle, 600-volt converters.

H. W. Buck (by letter): On a miscellaneous system of power transmission covering a large territory it becomes very difficult to adjust the voltage throughout the transmission network to suit everybody, where each customer is directly dependent on the line voltage at the point of delivery of the power. This condition becomes more pronounced as the length of transmission lines is increased. With a trunk line, say 200 miles in length, feeding branch lies here and there of considerable length, it is virtually impossible to maintain anything like a uniform potential on all parts of the system, nor is it possible to prevent wide fluctuations in the voltage at any given point. Sudden changes in load are inevitable, together with changes in phase relation. Such power systems should not be closely restricted in regard to line voltage regulation but should be free to deliver power, in the rough, so to speak, with voltage refinements made on the secondary distributing circuits. The power company should be allowed a variation in line voltage of 20% if necessary, or 10% above and below a mean. Such fluctuations might not be objectionable for many classes of power work, but would, of course, be prohibitive on lighting circuits. It becomes necessary, therefore, under these conditions to have the voltage of the secondary distributing circuits rendered independent of the line voltage, and motor-generators must be installed.

It is true, as pointed out by Mr. Lincoln, that frequency variation with a motor-generator installation disturbs the distributing generator voltage; but on large transmission systems having a heavy and diversified load, as is usual, good frequency regulation is not difficult. The loads on various portions of the system, and consequently the voltage at such points, may fluctuate widely, but in general the total resultant load at the main power house remains either practically constant or else changes so gradually that the governors can compensate for it with small change in generator speed.

As to the comparison between induction and synchronous motor-generators, while the induction type has certain advantages in starting, the synchronous type has other advantages of equal importance. In cases of momentary short-circuits on the system there will be a tendency for all the motor-generators and converters to drop out of step, due to the consequent drop in voltage. In the induction type the torque drops as the square of the drop in voltage, and a heavily loaded induction motor may therefore break down at a comparatively small reduction in impressed voltage. In the synchronous type, the field current of the motor being proportional to line frequency only, will remain constant under drops in line voltage, and will tend to keep up the voltage at the motor terminals, and maintain the torque. In this regard the converter has the same characteristics as the induction motor, in that its field current falls with the voltage of the line. In the writer's experience the motor-generators of the synchronous type hold in step better under line short-circuits than either converters or induction motor-generators.

The absolutely independent control of the voltage of the distribution circuit possible with the motor-generator combination affords many operating advantages, all of which cannot be listed on paper. The possibility of independent phase control with the synchronous type is of special advantage. On every alternating-current power system there must of necessity be many small induction motors in operation, and compensation for their low operating power-factor can only be obtained by means of some large synchronous motors on the lines. The introduction of single-phase railways as customers on large power systems, with the low power-factors of their circuits, makes this corrective influence all the more demanded.

O. B. Coldwell (by letter): Mr. Lincoln places " Reliability of operation " at the head of the list of points to be considered when making a selection of the most suitable machine for the connecting link between the high-tension transmission line and the low-tension direct-current distributing system. Unquestionably this is the point of most importance to those entrusted with the operation of a plant using such apparatus.

It has not been the experience of the writer that the converter has a decided advantage over a motor-generator set, on account of there being but one machine to get out of order rather than two. A converter is necessarily provided with slip-rings on the alternating end—six rings in the case of large converters—and even with the best of attention there will occasionally be trouble on this side of the machine. This feature is entirely absent in the motor-generator set.

The induction set is driven by a unit that, when once in operation, has a decided tendency to remain so in spite of momentary disturbances on the high-tension system which would invariably cause the synchronous motor and the synchronous converter set to drop out of step. Due to the intimate relation existing between the alternating-current supply circuit and the direct-current end of the converter—both being connected to the same set of armature windings—and to the fact that the sliding contacts on the alternating-current side are to be taken into account as well as the commutator, I should consider the converter as the least reliable machine when inherent defects in the apparatus are used as a basis of comparison.

I should therefore revise the table of relative reliability due to defects inherent in the apparatus to read as follows:

Induction motor-generator	10
Synchronous motor-generator	14.
25-cycle synchronous converter	17.

I agree with Mr. Lincoln that it is an advantage to be able to control the voltage independently of the supply circuit. Undoubtedly the converter is handicapped in this respect. In railway work this is not of such importance as in the case of lighting apparatus.

As to the "corrective effect," the synchronous motor-generator set is the only unit under consideration that can be used for the purpose and at the same time not suffer a disturbance of the direct-current voltage. Unless the "corrective" features of the synchronous motor and converter are applied intelligently, more harm than good may result.

The synchronous converter is the best machine as regards efficiency. Mr. Lincoln's calculation is apt and shows very plainly the advantage enjoyed by the converter in this respect.

Regarding cost, the writer is of the opinion that 60% is somewhat low for the converters, as it is necessary to consider the step-down transformers, the voltage regulators, the blower for air, cooled transformers, and the more expensive construction due to the necessity for an air chamber under the transformers.

Parallel operation is equally good for all machines.

The induction motor-generator set is the best as regards starting, as no synchronizing is required. In some of the larger sets, however, it is customary to start them on direct current and bring them to speed before connecting them to the supply circuit, thus avoiding any serious shock on throwing on the line.

No mention is made of the use of half or one-third or two-thirds taps for starting the converter on the alternating-current side. This is undoubtedly the quickest way of starting a converter and connecting it with the line. It is successfully used.

The use of the storage-battery in central sub-stations where a large direct-current, low-tension lighting system is installed, as well as a direct-current railway system, for the purpose of acting as a relay on the alternating-current supply from long-distance transmission lines, should in some cases have a bearing upon the selection of apparatus. In such case the battery could carry, during times of trouble, the low-tension system directly and the railway system indirectly, the transformer machinery being operated inverted.

While converters have been and are operated inverted, they are not so successful in this respect as the synchronous motor-generator set.

It is the writer's opinion that a selection of apparatus should be made only after a very careful study of all the operating features of the particular case in hand. It is quite possible that the best results could in some cases be obtained by using both converters and motor-generator sets. A discussion of this particular feature should bring out some interesting points.

W. R. C. Corson (by letter): The problem of determining the best method for converting alternating to direct current for any particular case must, of course, be largely dependent on the governing conditions of supply and the purpose of the derived current. Mr. Lincoln's treatment of the subject, by classifying the operating requirements of such apparatus, and noting the points of relative vantage which the several methods possess in each class, is an analysis which aids in a solution of the problem. But it is, after all, a problem which is not susceptible of a general solution. The several classes of operating requirements should be given differing relative values in considerations involving the choice of apparatus for differing purposes or conditions. The summary of Mr. Lincoln's paper, which seems to establish the preëminent excellence of the converter because it is found superior in a majority of counts, is, however, really of little assistance and serves only to establish an explanation for its present almost universal employment for the conversion of alternating to direct current. There are conditions of operation in which the synchronous converter falls behind its competitors in filling the essential requirements, and any conclusion that will help us in a limitation of these conditions will be useful.

Under the head of reliability, the synchronous converter is given the highest award, because but a single machine is involved as against a unit of two machines. The conclusion would follow that the converter is therefore twice as reliable as any method of double conversion, were it not for the further numerical values for the relative reliability advanced by the author. Now the relative reliability can hardly, it seems to me, be measured by the number of hours that the apparatus would be out of service within a given time, even if we could all agree on a basis for estimating the probable hours of breakdown. A more reasonable valuation of reliability would be the ratio of operating time to that of breakdown; but here again any exact assignment of values would be so much a matter of personal opinion that no definite conclusion could be reached. The mathematical chance of pure accident is greater in a unit of two machines than in a simpler apparatus, but reliability, from the practical viewpoint, should involve other considerations than the mere mathematical chance of accidents from unforeseeable causes. We must take the risk of accident, in this sense, in almost any responsibility we assume, and can rarely place a value on such risk.

Reliability, for the purposes of this discussion, should cover the broader field of ability successfully to operate under adverse or abnormal conditions, and the weight attached to the measure of reliability, as thus defined, possessed by any class of apparatus should be in proportion to the probable diversion from normal of the conditions for which a selection is to be made. Reliability, in other words, should be understood as the possession of robust characteristics as opposed to those sensitive to adverse conditions.

For general ability to withstand the hard knocks of fluctuations of voltage, frequency, or load, or of heavy overload, and to operate with a minimum of attention under all circumstances, the induction motor is without a peer. A direct-current generator coupled to it to form conversion apparatus can be designed to possess the best characteristics of such a machine uncompromised by the conditions imposed by the alternating-current supply. From the point of view of reliability I should, therefore, place the induction motor-generator set in first place; the synchronous motor-generator in the second; with full appreciation of its merits under proper environment, I should give the synchronous converter the lowest mark of the three.

The characteristics of the several types of converters as affecting the control or regulation of the direct-current voltage is considered by Mr. Lincoln, and his conclusion that relative numerical values of merit should not be attempted on account of the variable conditions dictating a selection is correct. He points out one case in which the synchronous converter can not be used; as no case appears against the other types, perhaps in this particular group of characteristics the converter must also take last place.

The corrective effect of the converting apparatus on the line is a matter of importance in the proportion which the capacity of that apparatus bears to the total load on the line. It is clearly shown in the paper that circumstances of control make this effect a desirable or undesirable characteristic. The induction motor-generator, having no corrective effect, may be, therefore, in this count, either utterly worthless or preëminently excellent, but under either consideration the converter seems to have second place.

In efficiency, the converter is undoubtedly the superior of either of the other types with which it is compared, and it is unquestionably its superiority in this respect which influences most largely its almost universal selection. It does not seem quite fair, however, to allow to the converter quite the measure of superiority credited by Mr. Lincoln's figures for efficiency. These, I understand, are admittedly made on the assumption that the line voltage is "too high for a revolving machine and must be transformed before utilizing." This assumption is of a condition which is usually necessary to converter operation but by no means so to that of its competitors. To give them the benefit of the doubt, it would be fair to decrease the figure representing the economical superiority of the converter by an amount determined by the static transformer losses. If this were admitted, the relative economy of the different types would be represented by the following values:

Synchronous converter	91
Synchronous motor-generator	85
Induction motor-generator	84

The first cost of a synchronous converter installation is much less than that of the other types, but again the cost of step-down transformers, and usually of additional switching equipment, should be included with that of the converter itself in the comparison.

The parallel operation of all types of machine under consideration can be accomplished successfully under normal conditions. Under certain abnormal conditions, however, either type of synchronous apparatus is more sensitive than the induction motor-generator.

In starting characteristics, Mr. Lincoln's analysis places the induction motor-generator set at the head of the list, the synchronous converter second, and the synchronous motor-generator last. The reasons for this rating appear sufficiently obvious.

In his summary, Mr. Lincoln concludes that as the synchronous converter excels in his analysis in counts 1, 4, and 5 and is practically at par with the best in count 7, there would seem to be "but few cases where the motor-generator should be used in preference to the synchronous converter." From my rating of the characteristics of the types considered, it appears that in counts 1, 2, 3, 6 and 7 a form of motor-generator is inherently superior to the converter, while only in counts 4 and 5 does the converter take unconditionally the first place. But counts 4 and 5 are usually factors of prime importance in the choice of apparatus, and the characteristics required by the other counts are possessed in sufficient degree by the converter. The conclusion is undoubtedly true, then, that but comparatively few cases exist where it should not be used. In fact the conclusion is so obvious that this discussion would be of little value, did it not, as it does, indicate by its analysis the conditions which would determine the selection of other apparatus in these few cases.

Where the synchronous converter is but one portion of an electrical system designed, installed, and maintained as a whole, for the particular purpose of the direct-current supply, the conditions most suitable for converter operation will be provided. The frequency, voltage, regulation, etc. will be selected with particular reference to the purpose of the conversion, and the control of all apparatus will be subject to one management, or at any rate to a common interest. In installations of this character, reliability of performance, adjustment of voltage, corrective effect on line, etc. will be maintained within the limitations of converter characteristics by the provisions of the entire system, and the manifest economy and low cost of such machine will secure its selection.

On the other hand, where the purpose of the conversion is merely incidental to the general purposes of the whole system, conditions less favorable to converter characteristics are more prevalent, and problems of selection will arise. In such cases, independence of purpose of demand and supply may often be best served by the electrical independence of the machine utilizing the supply and that supplying the demand.

So far as any general conclusions may be drawn from a discussion of this character, therefore, I would advance the proposition that the criterion of utility of either of the conversion methods considered lies in the degree of community which the purpose of the supply bears to that of the demand.

Henry Floy (by letter): It must be borne in mind that Mr. Lincoln's conclusions are very general and may not apply to any particular or individual case. A paper of this character is so frequently accepted as conclusive and universal application attempted, that I desire to show how unsuited these general conclusions may be in some cases. For example, it is practically impossible to use a converter, without storage-battery, to supply satisfactory lighting service at the end of a long transmission line that also serves alternating-current motors carrying large fluctuating loads, because the motor load will disturb the alternating voltage which directly affects the direct-current voltage. A motor-generator would therefore be necessary, regardless of the general conclusions, or the advantages claimed for the converter. Again, if the voltage of the transmission circuit were not so high as to prohibit the use of motor-generator sets without step-down transformers, a considerable investment, always necessary with a converter installation, would be saved.

Under the item of "cost" it seems to me that Mr. Lincoln has not clearly indicated the relative investment necessary, because the converter must be provided with some voltage-control apparatus that, from the comparative figures given, do not seem to be included in Mr. Lincoln's costs; moreover, if a motor-generator can be used without transformers, the converter installation with transformers and regulators will usually make the total converter cost higher than that of the motor-generator.

In a section where lighting is troublesome, I believe an induction motor-generator will be found much more satisfactory than a synchronous motor or a converter, because the induction motor will frequently pick up its load again without the shut-down of the other machines that will ordinarily result from the short-circuit caused by a lightning flash.

I do not agree with Mr. Lincoln in regard to the reliability of the different types of machines, for although the converter is but a single unit, it is twice as liable to some causes of breakdown as either a motor or a generator, because it is connected to two circuits—on its alternating and its direct end—and would therefore suffer, for example, from lightning coming in through either circuit.

Clarence E. Gifford (by letter): It goes without saying that insulation of apparatus operated from a motor-generator can not suffer directly from "surges" on the line from which power is supplied to the motor.

It is equally true that direct-current apparatus operated from converters often has its insulation subjected to very severe strains by such surges, especially surges that arise from momentary grounding of one of the lines of the supply system.

It will be readily seen how such a ground, or a permanent one, were it permitted to remain, may, and generally does cause a strain between the earth and any conductor connected with the secondary winding of a transformer supplied from a system upon which such ground occurs, or with any portion of a transformer or successive series of transformers which are operated by current received from said secondary. And this condition does not necessarily imply any change in voltage between the primary lines, one of which is grounded, although a change would doubtless occur.

The surge is transmitted through a transformer or series of transformers in the same manner as through a condenser; or in case of a ground of more than momentary existence, the entire secondary system would have its insulation from earth subjected to a series of strains recurring with the same frequency as that of the current. The primary and secondary windings of a transformer would in this case correspond to the plates of a condenser, and the action is not likely, in most cases, to be greatly modified by the core, unless it be well grounded.

Numerous experiences prove that the strain between earth and a direct current 220-volt system operated from a converter receiving power from a 22,000-volt system through three step-down transformations, often rises momentarily, when no preventive measures are adopted, to thousands of volts, and at a season of the year when the power company cannot say "lightning." In one instance two direct-current motors grounded at the same instant that the power company lost a cable, and from appearances one not familiar with such occurrences or with the circumstances would certainly have pronounced it the work of lightning. Incidentally, it is interesting to note the inventive faculty displayed by the "experts" of some power companies in assigning any cause but the true one for these expensive occurrences.

The best protection against such effects that the writer has found, and it has proved remarkably satisfactory in a trial extending over many months, is to place at various points in the direct-current system, notably near the converter, near the extremities of long trolleys and near stationary motors, carborundum resistances of 1000 to 1200 ohms (for a 220-volt system) bridged between the lines and having the center well grounded.

Ordinary resistance rods of a resistance of 250 to 300 ohms, such as used in lightning arresters serve well. Each one may have terminals of No. 10 or No. 12 copper wire attached by winding the wire once or twice round the copper plated terminal of the rod, twisting it down tightly and soldering it by dipping. The resistance of each, in ohms, is then determined marked upon it plainly with paint.

They are then sorted and made up in series of four, with all joints soldered, in such manner that the resistance between the center and one extremity of any series does not differ from that between the center and the other extremity of the same series by more than two or three ohms. Any other style of leakage devices used for the same purpose must of course be practically non-inductive, rugged, and so proportioned that when a dead ground occurs on one side of the local system the current flowing through the device shall be just safely below a point that would injure the device or its connections.

As before noted, the best protection for any local system operated from long-distance lines, is likely to be secured by distributing a number of such leakages at points where theory and experience indicate the greatest need. Unless the current value of a surge exceeds the ordinary, the potential between the system thus protected and the earth will not rise to a dangerous point.

As an indication of this fact, one plant in mind required five to eight new lamps per month for a ground detector, the lamps receiving normally only one-half full voltage, and this was not due to ordinary grounds on the system.

Since leakages, as described, have been provided, the detector lamps escape destruction, and crane operators cease to fear being knocked nearly senseless, as has occurred in the past, but the most noticeable result is the great decrease in number and seriousness of motor troubles.

Wm. B. Jackson (by letter): Under the list of "points" which are considered in the paper, it seems to me that the subject of "*Parallel operation*" should either be omitted entirely and considered as being covered by the subject "*Reliability*", or that it should be placed second in the list. Without perfect parallel operation "*Reliability*" as considered in the paper would be of little value.

1. *Reliability.* In this matter I take direct issue with some of the statements made in the paper. It is true that the the synchronous converter comprises but one machine, but it it is equally true that this machine is the weakest brother in the entire family of alternating-current and direct-current machinery. It is formed from a combination of a revolving armature alternating-current synchronous motor which, considered as an alternator, is no longer an acceptable piece of machinery, and of a direct-current generator which has been designed, not as the best possible direct-current generator, but as the best generator that can be made a component part of a synchronous converter.

The argument against the motor-generator set on account of pressure and insulation would be more nearly correct if reversed, for there can be no reason for using a higher voltage on the alternating-current side of a motor-generator set, unless it has evident advantage over the lower pressure. Furthermore, a first-class stationary armature induction or synchronous motor can be safely insulated for several times the pressure that can be employed in a synchronous converter armature with equal safety.

Although, as stated in the paper, the fault of "bucking" is not one of very serious moment in present day practice, yet this fault can be eliminated with greater ease and certainty in a simply direct-current dynamo than in one which must also work in with an alternating-current frequency of even 25 cycles, and this fact is emphasized if 60 cycles is considered.

2. *Voltage regulation.* I am unable fully to agree with the conclusions arrived at under this heading. I do not consider that, "All methods under discussion are equal" for "automatic change in voltage with change in load" for the reason that the automatic results that can be obtained in the synchronous converters are dependent upon various extraneous conditions while such results are obtained in motor-generator sets with the same simplicity as in any direct-current dynamo, for the direct-current side of the machine, and in the synchronous motor-generator set very effective regulation on the alternating-current side can be obtained with simplicity and without interaction with the direct-current operation of the machine.

In considering the "ability to adjust the initial voltage" it is impossible to accept the statement that the introduction of an alternating-current booster on the converter shaft is a more "logical arrangement so far as initial voltage is concerned than the motor-generator." Such an arrangement with its regulating rheostat and switches certainly does not constitute so logical an arrangement for voltage regulation as a simple rheostat in the field of a direct-current generator.

In considering "variations in direct-current voltage with variations in incoming line voltage and frequency" I agree in general with the conclusions arrived at, though I consider that too much relative importance has been given to the difficulties arising from variable frequency. In most up-to-date transmission plants where the "line voltage is too high for a revolving machine and must be transformed before utilizing", the problem of maintaining uniform frequency has been solved, though this cannot be said as regards the problem of uniform delivered voltage.

Under "Corrective effect" my views agree with those expressed in the paper, though it should be added that in the case of almost all high-tension transmission plants there is direct telephone connection between the power house and all sub-stations containing current-transforming apparatus. As these sub-stations usually require continual attendance, they thus become a valuable adjunct of the transmission system, and especially so if synchronous motor-generator sets are used therein.

4. *Efficiency.* There appears to be an error in computing the additional value of synchronous converters as compared with motor-generator sets, when considered simply from

the standpoint of relative efficiency. The capitalization of the saving due to the higher efficiency of the synchronous converter is made upon a basis of 6 per cent, while in fact 10 per cent. is the least figure that should be used in this connection. This would be upon the basis of 5 per cent. interest upon the money involved and of 5 per cent. for depreciation or sinking fund.

There are some factors that enter into this consideration which have advantageous bearing upon the motor-generator set, and have not been considered in the paper. In sub-stations supplying mixed service, uniform step-down transforming apparatus can frequently be used for all classes of service when motor-generators are employed, while two ratios of transformation must be used if synchronous converters are operated. Also in the case of very large converter units, the handling of the great quantity of alternating current at from 350 to 450 volts which is required is sometimes a factor of considerable importance.

There are also cases where, even for plants of the class here considered, an extra set of transformers must be provided for synchronous converters that would properly be omitted in the case of motor-generator sets. Such a condition is presented where the high transmission voltage must be reduced at the outskirts of a city to permit of carrying the current into the distributing stations located in the city.

5. *Cost.* Under this heading the same additional considerations that are presented under "*Efficiency*" should be taken into account to arrive at a fair analysis of the relative importance of synchronous converters and motor-generator sets, when considered from a broad point of view.

6. *Parallel operation.* Although it is true that troubles from imperfect paralleling qualities are not of frequent occurrence in up-to-date transforming machinery, yet the motor-generator sets have the advantage. In fact during those times when unending troubles seem to come upon the operating superintendent in a bunch, as they sometimes do in the best regulated plants, the synchronous converters are usually the first to show signs of distress, and this is especially true in plants of higher frequencies, while motor-generator sets are not so prone to crankiness. In motor-generator sets, troubles arising in the direct-current side of the system cannot have magnetic or electrical effects upon the alternating-current side, nor can troubles arising in the alternating-current side have such effect upon the direct-current side. This cannot be said of synchronous converters.

7. *Starting.* The question of starting has been well presented, but considering that an error in starting is likely to cause vital trouble in the synchronous converter on account of its commutator and collector rings, and also that the revolving-field synchronous motor properly connected to a high-class direct-current generator is a more robust piece

of apparatus to withstand synchronizing mistakes, it does not seem fair that the synchronous converter should be placed ahead of the synchronous motor-generator set as regards starting qualities.

Summary. In the foregoing, I have more particularly considered the advantageous qualities of the motor-generator set, as it had seemed to me that the advantageous features of the synchronous converter have been very fully presented in the paper. There has been no thought of belittling the field of usefulness of the synchronous converter. At the same time, I do not feel that the phrase in the "*Summary*" "that there are but few cases where the motor-generator should be used in preference to the synchronous converter" should go unchallenged. In fact, there are large appropriate fields of usefulness for both the motor-generator set and the synchronous converter, though it is fair to admit that the conditions will doubtless warrant a greater number of synchronous converters than of motor-generator sets being put into service.

R. S. Kelsch (by letter): The writer has used both motor-generators and synchronous converters. There can be no rule which makes one better than the other. Local conditions, class of service, number of units, and the characteristics or nature of the system from which they are operated entirely govern the advisability of using one or the other.

Farley Osgood (by letter): We are operating ten converters driven by current from our power station and transmitted about 60 miles at 33,000 volts at a frequency of 60 cycles. Four of these converters are 30 miles, three are 45 miles, and three are about 60 miles from the power station, and are placed in three different sub-stations, and, at times, all operated together.

These being 60-cycle machines, I presume they are the most sensitive type of synchronous converter in use. We find that these machines are very reliable, and, generally speaking, the interruptions to service are caused by the flashing-over at the brushes on the commutator. These machines have been in service for three years.

The first year's experience with the converters brought them into ill repute as regards reliability; but a careful study of the situation showed that the real difficulty was the lack of voltage regulation on the generating end. Regulation conditions were bettered by means of the water-wheel governors, and the installation of a voltage regulator. Since the correcting of the voltage regulation, or during the last year and a half, the ten converters have thrown themselves out of service less than ten times, giving an average of better than once per year per converter. I think this is as good a record of running as can be shown by any other type of machine driven from a source of power of high voltage and used for railway work.

These machines are 430 volts on the alternating-current side, and furnish 600-volt current on the direct-current side. They are connected with the high-tension system of 33,000 volts by means of a step-down transformer with a reactance coil in series between the transformer and converter.

Our experience shows that converters with bad voltage regulation on the alternating-current side are the worst things an operator can have; but with good voltage regulation, which with existing regulating appliances is wholly possible, the converter is entirely satisfactory and preferable to the other two types of machines under discussion.

Our experience with the converter also brings out the fact that although a sudden rise of 10 per cent. of the voltage from the generating source is liable to make the converter flash-over, a very great drop in the generating voltage may occur without affecting the converter.

Three times we have had a generator oil-switch stick so that the machine was thrown in and out of service several times in rapid succession, and so disturbed the line voltage as to lower it on the indicating voltmeter from 110 to about 65, and yet on none of these occasions were the 60-cycle converters thrown out of step so that they went out.

Concerning the "*Corrective effect*". When the load of our system is so arranged that the power and lighting load is carried on one transmission line, and the railway load on the other; in other words, when there are only induction machines on one line, we have materially to increase the voltage on this line in order to bring about any satisfactory power-factor. In mixed service work, therefore, the converter will help the voltage at the generating end by bringing about a more satisfactory power-factor. We find that an induction load only will perhaps require an increase in potential of from three to five per cent. at the generating end, but by placing converters with the induction motors satisfactory results are obtained on the receiving end without this increase in potential, This is simply an actual operating condition mentioned to bear out a well-known theoretical supposition.

Concerning "*Efficiency*". The experience on the system here, which carries converters at three sub-stations at a total transmission length of 60 miles, shows that with the proper arrangement of load we can obtain the power-factor as indicated by Mr. Lincoln; namely, 95 per cent.

Concerning "*Parallel operation*". We find no difficulty in operating our 60-cycle converters in parallel, not only with each other in the same sub-station, but in parallel with other converters in other sub-stations. At first the converters did not all appear to be of equal efficiency; it was found, however, merely to be a matter of adjustment, the large apparent differences of efficiency being easily done away with

One noticeable feature in a converter, which, however, is probably a well-known fact, is that the different phases of any one converter will not require the same amount of current, and that the various phase requirements vary.

As we use single-phase recording watt-hour meters to measure the current taken by the converters, we can very easily observe the current requirements of each phase of the machine. Often the meter will change its speed in favor of another phase of the converter sufficiently to be observed by a man watching the meter discs. The daily record of consumption taken from these meters shows swings from one phase to another from one day to another.

In summing up these discussions, I would say that I would not recommend any type of machine other than a converter for railway work from a high-tension source of power.

John C. Parker (by letter): The writer has been much interested in the particular phase of voltage regulation that bears on the distribution of load between various machines and between systems fed by distant hydroelectric generating stations on the alternating-current lines and engine-driven or local hydraulic plants on the direct-current lines.

In any large works or city distribution, it is customary to generate at a high voltage, 2500 to 11,000 volts, and distribute by means of this voltage to various sub-centers, where transformation to either the railway or light and power circuits is effected. The motor-generator set possesses, in such a case, one decided advantage over the more ordinary form of synchronous converter, in that the load taken on by any one station may be varied by manipulating the field excitation of the generator without influencing the power-factor of the alternating-current lines, and vice versa. Thus, during a period of maximum activity in any one section of the distribution system, the direct current voltage may be depressed, causing more distant sub-centers to feed into and relieve this particular district by means of the direct-current network, whereas with synchronous converters the tendency is for the converter nearest the concentrated load to assume increasingly greater proportions of the load until its automatic apparatus cuts it out of service. Of course, the inherent regulation of the converter can be made so bad as to give a strong drooping characteristic even at a good power-factor, but this is evidently at the expense of the copper efficiency and leads to voltage variations which are manifestly objectionable—especially on lighting systems. With the motor-generator set, the load fluctuation can be guarded against and the direct-current voltage regulation at the same time kept reasonably near what it should be, by designing the generator so that the voltage will progressively rise with increasing loads, until at any desired load point it begins to drop and thence rapidly decrease to a value below the no-load voltage, thereby causing current to flow in from distant transformation points which may be less heavily loaded.

Inasmuch as hydraulically generated power must be sold on what is in all cases the equivalent of a peak-load basis, we often find installations in which 24-hour power is received from a distant hydroelectric plant and is supplemented, on the peak, by a local steam generating plant. In such a case the vagaries in the transmission voltage or momentary peaks in the load demanded on the direct-current system may result in a heavy overload in the alternating-current transmission. A few of these peak overloads will heavily affect the consumer's bill. Here again the synchronous converter suffers a disadvantage that cannot be obviated otherwise than by juggling with the power-factor, which is manifestly prejudicial to the distribution system. A motor-generator set having a slightly rising voltage characteristic on the generator up to normal load, followed by a rapid droop, tends to take a more nearly constant load. Such characteristics are additionally important when the voltage regulation of the steam-driven local plant is bad.

It should be pointed out that the alternating-current booster or induction regulator referred to under caption two of Mr. Lincoln's paper, permits the application of automatic relays to the system for accomplishing such load control, and indeed permits a more direct regulation of load than can be obtained with motor-generator sets. On the other hand, this introduces additional elements of unreliability into the system, one of which, the relay, is especially delicate, while the induction regulator must be very substantially designed if it is to stand up under the severe treatment to which it is subjected. It is obvious that neither of these methods permits so nearly instantaneous operation in the division of load as does a motor-generator.

The elements of relative efficiency and cost would seem to be a function, more or less, of the specific voltage used in distributing to the various transformation units. If, for example, it were necessary to use such a subsidiary distributing voltage as 2500 or 11000 volts for works distribution, or for entrance to and distribution underground in a city, the element of transforming cost would be eliminated in the case of the synchronous or induction motor-generator which might operate directly at either of the voltages mentioned, while additional transforming equipment would have to be used with the synchronous converters. In all probability, this would still leave somewhat of a margin in both the matter of efficiency and of cost in favor of the synchronous converter, but probably not a very large margin. If in addition, an alternating-current booster or induction regulator were installed, the efficiency and cost, as well as the reliability of the converter, would suffer somewhat additionally. The complexity of the equipment would also be materially increased. The writer is inclined to feel that a distributing system of 2500 volts would show a worse case for the synchronous converter than would a distribution voltage of 11,000, inasmuch as this higher voltage would react much more prejudicially on the cost, efficiency, and reliability of the synchronous motor than it would on the transformers which would probably—following the modern practice—be made oil-insulated for this voltage.

In a number of cases a material advantage accrues to the motor-generator set from the less room it occupies as against the synchronous converter, step-down transformer, and—if this feature were included—the alternating booster or induction regulator. Whether this and a few other elements mentioned would throw the balance one way or the other between the two types of apparatus, would seem to be a question controlled by the special considerations in any given installation, such as the size of units and voltage on the distributing alternating-current transmission system.

H. F. Parshall (by letter): The synchronous converter is the more advantageous machine to use when the conditions of transmission and distribution are such that the ratio between direct-current and alternating-current voltage is more or less fixed. When the line drop is considerable, and a constant or increasing direct-current voltage, according to load, has to be maintained, the synchronous converter is at a disadvantage. When however, the reverse is the case, the synchronous converter has the advantages of higher efficiency, less first cost, and, in favorable cases, greater capacity for extreme overload. The motor-converter stands in an intermediate position between the motor-generator and the synchronous converter. It has not the flexibility of the motor-generator in the matter of voltage transformation and has not the high efficiency of the synchronous converter. Now that the development of computating machines for high speeds to suit the requirements of turbo-machines, is assuming a satisfactory status, it appears very reasonable to suppose that, in most classes of long-distance transmission, the balance of advantages will lie in the use of motor-generator sets. In other cases, however, where the ratio of transformation can, from the nature of things, remain more or less constant, the balance of advantages will lie with the synchronous converter, so far as efficiency and first cost are concerned.

A. C. Pratt (by letter): While Mr. Lincoln's analysis of various means of obtaining direct current from transmitted alternating current is fairly stated, it must be borne in mind that the choice of a proper medium will depend largely on the governing conditions of the particular installation. In all systems reliability is essential. While 25-cycle converters are satisfactory, 60-cycle converters may be termed successful. But they are not always a comfort to the operating engineer and are certainly more apt to develop internal troubles or go out of step when slightly unfavorable conditions arise, than are induction or even synchronous motor-generators.

In the operation of converters there seems good reason for providing separate motor-driven exciters, in which case voltage fluctuations not accompanied by change of speed will have much less effect on the operation.

In many long transmission systems voltage regulation or corrective effect, singly or together, are the governing conditions when designing a sub-station. If converters are used, either one of these features may be provided for with reasonable success; but it is by no means easy to cover both at once in such a way as not to affect other branches of the system unfavorably.

A poor power-factor in the transmission system may readily cause a greater drop in over-all efficiency than the difference between the efficiency of converters and motor-generators, provided the latter results in a good power-factor in the system. The ideal system transmits power current only; the idle current needed at various consuming points is generated at these points; permitting less capacity in generators, transformers, and transmission line, and better regulation at the consumer's end. The synchronous-motor generator in large size units with a motor of unusually ample size offers means of attaining closely the ideal system.

Steadiness of speed is usually much better maintained than steadiness of voltage on a transmission system; therefore the generator of a synchronous motor-generator set will regulate well, and a first-class regulator applied to the exciter of the motor will afford the corrective effect for the alternating system. Under these conditions, alternating-current lighting and direct-current railroad load can often be supplied from the same bus-bars with excellent results. It must be borne in mind that the synchronous motor-generator requires slightly more intelligent supervision than induction motor-generators, but not more than the converter. For best results, therefore, the synchronous motor should be used under immediate supervision of the transmission company.

Another item for consideration is the character of the direct-current load as regards inertia effects. Some loads, like lighting, store no energy, while some motor-driven loads store a large amount of energy when coming up to speed. Assuming a load of the latter type, supplied from induction motor-generators, and a momentary short-circuit cleared by time-limit circuit-breakers on some one feeder out of the sub-station. During the short-circuit the induction motors will slow down much more than will the generators at the power station. The sudden removal of the short-circuit will cause a sudden rise of voltage, which in turn will cause a rush of current to the induction motors; these, hampered by large inertia, will very likely trip their breakers before attaining normal speed, or the speed will have dropped so low that the motor torque is reduced to a point below full-load torque, in which case there is little probability of recovering the load.

Under the same conditions, if the short-circuit is not too severe, a synchronous motor having a high "pull out" torque will stay in step and hold its load. This observation applies also with especial force to induction motors, of relatively low "pull out" characteristic loaded with heavy shafting or air compressors, in which case the load torque is not reduced as speed is reduced The same motors would show entirely different results when driving centrifugal pumps.

Leo Schüler (by letter): It may be interesting to discuss the subject of this paper from the European point of view, as there is so distinct a difference between American and European practice. I dare say that on this side of the Atlantic the number of converters in operation does not exceed one-tenth the number of motor-generators, while I think that in the United States the opposite ratio may safely be assumed. As a matter of fact, I do not consider the author's conclusions, which are generally in favor of the converter, to be quite impartial, and for the following reasons:

I see no reason to assume "a somewhat variable frequency." Governors for all kinds of prime movers can certainly be obtained so as to keep the speed constant within one or two per cent. and with proper care variations of frequency of more than one per cent., can certainly be avoided. We may therefore safely assume a virtually constant frequency.

The author assumes "the line voltage to be too high for a revolving machine." this means more than about 15,000 volts; as such voltages are only employed in long transmission lines, it seems only fair to assume further that a considerable drop of pressure takes place on the line, say 20-25 per cent. It should be well understood, that with a lower pressure the comparison would be more in favor of motor-generators, as static transformers could be avoided.

1. *Reliability.* I do not understand why "with the motor-generator, other conditions may dictate a very much higher motor-voltage," as static transformers are distinctly specified.

It is true that under normal conditions the possibility of "bucking" is about equal with 25-cycle converters and direct-current generators. It must be kept in mind, however, that the sparkless running of the commutator in a generator depends only upon the direct current taken from it, while in a converter it is also affected by the conditions of the alternating-current system. The 60-cycle, 600-volt converter has necessarily such a high pressure between adjacent commutator segments that it must be set quite at the other end of the reliability list.

As I consider the synchronous-motor to be a little more reliable than the induction-motor, in consequence of larger air-gap, I should figure the reliability to be about as follows:

25-cycle synchronous converter Synchronous motor-generator	12 hours.
Induction motor-generator	14 hours.
60-cycle synchronous converter	25 hours.

2. *Voltage regulation.* There can be no doubt but that the direct-current voltage supplied by a motor-generator depends only upon the direct current taken from it, while in the case of a con-

verter it is greatly affected by the alternating-current voltage.

It must certainly be assumed that the alternating-current voltage supplied to a sub-station by a long transmission line is variable, not only in consequence of the variable power consumed in this individual sub-station, but it also affected by other sub-stations, starting of motors, working of lightning-arresters etc. in any other point of the system. As the effect of all compounding arrangements, with or without reactance or boosters, is based on the magnetizing effect of the direct current taken from the converter, they certainly will not respond to independent fluctuations of the alternating-current voltage. It is therefore impossible with converters to obtain automatically a constant direct-current voltage with a variable alternating-current voltage; this reason alone, I think, simply forbids the use of converters for lighting purposes in connection with long transmission lines.

Summary. As the converter has certainly a distinct advantage with regard to efficiency and costs, while there is practically no difference with regard to starting, I would summarize as follows:

For 25-cycles, railway or other motor circuits, converters are always preferable. For 60-cycles, motor-generators are more reliable and should be adopted if costs and efficiency are not prohibitive, especially if the primary pressure is low enough to allow omission of static transformers.

For lighting circuits, converters are applicable only if the alternating voltage itself is sufficiently constant for lighting purposes.

Carl Schwartz (by letter): *General.* Synchronous converters are extensively used where three-phase alternating current of high potential and a frequency of 25 cycles is to be transformed into direct current. For the other higher standard frequency of 60 cycles, this type of machine is not nearly so satisfactory in operation as a motor-generator. As reliability is of prime importance, particularly in long-distance transmission, and as a synchronous or induction motor-generator is much more reliable, the converter does not need to be further considered in case of this or similar high frequency.

Mr. Lincoln clearly and briefly enumerates the various advantages and disadvantages of the three types, but on account of the great amount of detail to be considered it is impossible to balance the characteristics of the different constructions entirely against each other without taking specific cases; therefore the choice of one type or the other will always be governed by the prevailing conditions. If this were not the case, the choice could be left to the purchasing agent instead of to the engineer.

The following suggestions are offered to illustrate that a somewhat different point of view may change some features of one type to the advantage of the other.

Reliability. Mr. Lincoln considers the converter the most reliable machine, quoting as an advantage that there is only one machine instead of two, and that a low alternating current voltage has to be applied. As it is assumed that in both cases step-down transformers are to be used, there seems to be no reason for applying an unsafely high voltage in case of a motor-generator; in this respect, then, both types should be considered equal, inasmuch as the voltage for a motor-generator could be much higher than for the converter, without impairing its safety beyond the comparable limit. The chances of a breakdown may seem twice as great, because the motor-generator contains two rotors and two stators, while a converter has only one armature, and one set of field coils. The machines are, however, practically alike otherwise, assuming that the motor-generator has two bearings only. If the case warrants, spare armatures and field coils can be kept in stock, minimizing the consequences of a break-down.

An induction motor is less affected by line troubles than either of the other two constructions; on a long line this motor is most undesirable, and in figuring on this type of machine, the increased investment in copper or capitalized line losses should be charged against it.

Voltage regulation. With reference to voltage regulation, the converter is at a serious disadvantage. Boosters, potential regulators, or other devices in connection with the converter are undesirable additions, and influence items 1, 4 and 5, and, to a certain extent, item 3, in favor of the motor-generator. These complications were apparently not taken into account when comparing the machines in regard tor eliability, efficiency, and cost. The efficiency of the converter will be decreased by from one or two per cent., and its cost increased by from ten to twenty per cent., so in trying to make the converter equal to a motor-generator in regard to voltage regulation, its advantages may be counterbalanced to a large extent.

Efficiency. In considering the additional costs of current for the motor-generator against converter, inclusive of the regulator, and assuming an efficiency of 85% and 91% respectively, the following is submitted:

A low efficiency increases the direct operating expenses in coal, water, wages, etc., but not the fixed charges, as the power station will hardly be built larger on account of a slightly lower efficiency of transforming-devices. The cost of current per kilowatt-hour can therefore be estimated perhaps closer to one-half than one cent., decreasing the annual additional costs for current in case of the motor-generator to about $950. In capitalizing this amount, depreciation and other fixed charges should be included, for the reason that if the amount capitalized is invested in equipment it will have to be treated like other portions of the system.

Using 10% to cover all fixed charges, the annual extra costs for current represent an investment of $9500, or $19.00 per kilowatt capacity. The exact amount will depend on local and other conditions, and the difference may be still lower; for instance, in case of a water-power plant, or if the operating costs should otherwise be lower than five cents.

In most instances it will be almost impossible for the engineer to decide definitely which type of machine should be selected, before bids have been obtained, based upon specifications, outlining carefully all requirements, and leaving room for the manufacturer to specify the characteristics of the equipment he is able to offer.

Guido Semenza (by letter): The only point not put forward in this paper is, perhaps, the one excluded by the assumption "that the line-voltage is too high for a revolving machine and must be transformed before utilizing." This is often not the case, at least in Europe, where synchronous motors wound for 12,000 volts are in regular operation. Some firms would not hesitate to construct them for still higher voltages.

In such cases the cost of installation, the floor space occupied, the switching apparatus, and the efficiency of the motor-generator set are not very different from those of a converter with its transformers. Thus for primary voltages up to 8000 volts, in view of its other advantages, the motor-generator is generally preferred.

In Europe the use of converters is not so general as in the United States. This machine has been highly perfected in America, and its advantages have been only lately acknowledged on the old continent. Then again, for countries where hydraulic power is available, and long-distance transmission is the rule, there are special reasons for the preference being given to motor-generators, as I shall try to explain.

In the matter of power transmission and distribution many differences exist between one plant and another. We have, for instance, power plants of the type of the New York Edison Company's, in which the alternating current generated is mainly converted to direct current in a number of sub-stations belonging to the same company. The alternating voltage is then very carefully controled in the power house, in order to obtain the best direct-current regulation, and all systems used in the different sub-stations to control the voltage are there working in the best condition.

Assume, for example, a long-distance power transmission, say 100 miles long, from a waterfall. Consider that the power is sold in the neighborhood of the station, at the end of the line, and along the line. Suppose further, that there is a steam station working in parallel for overcoming the winter peak. We see that these conditions are quite different from those of the first instance, and voltage regulation cannot be done except to take care of the converter sub-stations.

In such a type of plant, rather common in Europe, converters can be put in for railway work, but it would not be very easy to obtain a good direct-current lighting service. In such cases motor-generators are preferred.

In plants of the above kind, the "corrective effect" of synchronous machinery, if any be used, is very important in order to correct the low power-factor given by induction motors. What Mr. Lincoln says on this point is quite right: it is much easier to control the corrective effect with synchronous motors than with converters in which the corrective effect and direct current are interdependent. I would let customers use synchronous motors, and I would not allow them to use converters on a somewhat complicated distribution plant, as they would only take care of their direct-current regulation without paying any attention to the power-factor.

Another matter in connection with long-distance transmission is the parallel running. It is well known that when the ohmic resistance of the line is too high, also good synchronous machines are apt to hunt and sometimes to such a degree as to get out of step. This is an extreme condition, but a certain amount of hunting may easily occur.

It is also known that by adjusting the excitation this hunting may be reduced. It is evident that in these conditions the motor-generator offers a great advantage, as this regulation can be done without affecting the direct voltage.

All these considerations show that the problem proposed cannot be solved in a general way: there are conditions in which the converter is, no doubt, the best adapted machine; there are others in which only a motor-generator ought to be used, and others also in which the use of either is equally as good.

On the comparison of synchronous versus induction motors, I must say that for driving-current dynamos the synchronous motor is in a general way, for many reasons preferable. It is not always true that after a momentary removal of the voltage from its terminals the induction motor will resume operation automatically: if it is well loaded it will often shut down and cause its own circuit-breaker to open when the voltage is restored.

The use of induction motors has to be resorted to only in case starting from the direct-current side is not possible. When starting on the alternating-current side causes too much trouble, and in the case of very long transmission lines where some difficulties are experienced with parallel running.

B. C. Shipman (by letter): *Reliability*. If reliability were the sole requirement of the problem, the induction motor-generator would, in my opinion, be the best transforming apparatus to use. Mr. Lincoln states no defects under this head against the induction motor-generator, except that higher voltages than 700 on the motor may be required by certain conditions. If the choice were between synchronous converters and induction motor-generators on the ground of reliability alone, certainly whatever voltage was available for a synchronous converter would also be available for the induction motor-generator. Therefore there would be no advantage on this point for either piece of apparatus. Of course it might be much more desirable to use a higher voltage, and the induction motor-generator would lend itself readily to this condition. Even so, I think the latter apparatus would still be on a par with the synchronous converter, as it is much more easily insulated and less susceptible to injury than a commutating machine.

The strong point of the induction motor-generator is pointed out in the paper; namely, automatic resumption of operation after an interruption to the service. All the weak points of the synchronous converter, however, are not covered. Synchronizing takes more or less time, certainly more than it takes to get an induction motor on the line, and it has to be done more frequently. "Bucking" of a synchronous converter also takes place more frequently than of a similar direct-current generator, for several reasons aside from the sudden removal of load. "Pumping", or even sudden aperiodic changes of speed in the prime movers, will cause a synchronous converter to "buck". In such cases there is a shifting of the field similar to that caused by the sudden removal of load. A synchronous converter, is also more often reversed by bucking than is a direct-current generator; hence its greater tendency to bucking counts considerably against its reliability as compared with a similar direct-current machine. Therefore I would change the numbers given in Mr. Lincoln's paper showing the relative amounts of time the respective machines are out of service, as follows:

Induction motor-generator...........	10
25-cycle synchronous converter........	14
Synchronous motor-generator...........	17

Voltage regulation and corrective effect. I concur in all the author's remarks under these heads. I have noted excellent regulation of direct-current voltage from a synchronous converter equipped with an induction regulator, when supplied from generators whose other load was street railways.

Parallel operation. Of course with similar units, parallel operation presents no difficulties or disadvantages of [one type over another. Sometimes, however, if a synchronous converter or a synchronous motor-generator is operated in parallel with an induction motor-generator, there is trouble in making the units divide the load properly throughout the full range. Assuming a constant frequency and voltage, the induction motor-generator will have to be compounded decidedly more than the direct-current end of either synchronous unit. A variable frequency or voltage, or both, will interfere with any fixed adjustment, so that under the conditions laid down in the paper under discussion, hand regulation would probably be necessary to effect good distribution of load between units.

Summary. In general, I agree with the author that in the majority of cases with conditions under discussion, the synchronous converter has the advantage.

Miles Walker (by letter): I am interested in Mr. Lincoln's paper on account of the discussion which has recently taken place in England between the advocates of the converter on the one hand, and the advocates of the motor-generator and the cascade motor-converter on the other.

It is mainly in the case of 50-cycle and 40 cycle-transmissions that difference of opinion exists as to the merits of the various types of machines. In the case of 25-cycle transmission the superiority of the converter for most purposes is generally admitted.

The Bruce Peebles-La Cour cascade motor-converter is now much used in England for transforming 50-cycle alternating power into direct-current power. On the other hand, the 50-cycle converter is also widely used, and the excellent performance and great stability of modern designs are fast overcoming the prejudice which existed in England against high-frequency synchronous converters.

In most cases where the matter is discussed in England, it is not permissible to assume that the line voltage is too high for a revolving machine and must be transformed before utilizing, because generally the line voltage is only 6,600 or 11,000, and with motor-generators the use of transformers is obviated. Notwithstanding this advantage in favor of motor-generators and motor converters, it can generally be shown that the use of transformers and converters is preferable on account both of reliability and economy.

Reliability. The risk of breakdown of a converter and its transformers is less than that of a motor-generator set. If one transformer out of three breaks down, it is possible to run with only two, and it is easy to substitute a spare transformer. It takes a long time to rewind a motor-converter.

I have seen a 50-cycle converter take six times full-load current momentarily without " bucking " or getting out of step, so it cannot be said that it is a delicate machine. It will not, however, stand a dead short-circuit.

I know of a case where three 1000-kw. 40-cycle converters have been installed for electrolytic work where continuity of service is of vital importance, because in case of a shutdown some hundreds of cells of molten electrolyte have to be refilled from a furnace at enormous cost. The plant has now been in operation six months without any failure on the part of the converters, although some motor-generators alongside of them have already been out of service more than the 17 hours allotted to them by Mr. Lincoln.

Voltage regulation. I agree with what Mr. Lincoln says in this division of the subject. The method of introducing self-induction into the transformers is applicable to most cases where a range of only 10% is required in the adjustment of the direct voltage. The power-factor on load need not be varied more than between the limits of 95% lagging and 95% leading current. In many cases the required adjustment is only 5% and the power-factor need not depart more than one or two per cent from unity. Very few users object to a leading power-factor, particularly at heavy loads.

Corrective effect. I agree with what Mr. Lincoln says in this division of the subject.

Efficiency. In dealing with this matter in England, we have generally to consider the losses in the transformers as well as in the converters, because these are in competition with cascade motor-converter sets on which very high efficiencies are guaranteed (93% on the 500-kw. size).

The converter and transformers are however still ahead in efficiency. It is safe to guarantee 94% on the 500-kw., 500-volt rating for the over-all efficiency of the converter and transformers and this without rating up the converter so high as to spoil the overload guarantees.

A well-designed 50-cycle converter can take very heavy overloads without commutation or heating troubles. It is therefore safe to keep it loaded to the full in cases where it would not be advisable to keep motor-generators fully loaded on account of fear of sudden demands for power, so that in taking the all-day efficiency of a converter, it is fair to take the efficiency at a higher percentage of the load than with a motor-generator. Here is a case in point: at a certain sub-station belonging to the North Eastern Railway Company the load fluctuates between almost zero and 1600 kw. A load of 1200 to 1600 kw. lasts at times for about one minute. The whole of this load is taken by one 800-kw., 40-cycle converter. Compare the efficiency of this sub-station with what it would be if the converter were replaced by, say, two 500-kw. motor-generators.

J. B. Whitehead (by letter): Under the author's assumption that transformers are used with all three types of machine, his conclusions appear reasonable. Attention may be directed, however, to the many instances of moderate transmission distance and voltage in which it is possible to apply the line voltage directly to either type of motor-generator, but to the converter only through the medium of transformers. The relative position of the motor-generator under such circumstances is bettered, not only as to reliability, but also as to efficiency and cost. Considering reliability, this improvement would be greater in the case of overhead than in the underground transmission in cities. The figure for the efficiency of transformer and converter becomes about 91%, the figures for the motor-generators remaining the same. The relative cost will now be approximately: converter and transformers 82%, motor-generators 100%. In many instances these differences may be sufficient to outweigh the more general choice of the converter, and indicate the motor-generator as the proper machine.

A paper presented at a special meeting of the American Institute of Electrical Engineers, New York, March 22, 1907.

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INTRODUCTION TO DISCUSSION ON THE PRACTICABILITY OF LARGE GENERATORS WOUND FOR 22,000 VOLTS

BY B. A. BEHREND

With the increased capacity of individual units of alternating-current generators it is natural that the potential for which these generators are wound should be continually increased. It commends itself to limit the current capacity of generators, as the distribution and conduction of large currents from the generators to the switchboards is cumbersome and expensive. Historically, the increase in voltage with the increased capacity of individual units and of power plants may be briefly summarized. The Niagara generators of approximately 3500 kw. capacity, put into operation about ten years ago, were designed for 2200 volts. The 3500 kw. generators of the Metropolitan Street Railway Company, of New York, were designed for 6600 volts. The 5000-kw. generators installed in the stations of the Interborough Rapid Transit Company, in New York, were designed for 11,000 volts. The large generators for the Brooklyn Rapid Transit Company, of 7500 kw., were designed for 11,000 volts also.

The question of the importance of higher voltages in future plants cannot be discussed without reference to prime movers. The four types of prime mover which are likely to be of great importance in the immediate future are:

1. The hydraulic turbine.
2. The gas engine.
3. The reciprocating steam engine.
4. The steam turbine.

1. The field of the hydraulic turbine for large capacities, by which I mean capacities of 7500 kw. or above in individual units, is not likely to be of great importance at the present.

2. The gas engine has been successfully built for capacities up to 2000 kw. and while it has unquestionably a great future for greater capacities, nothing as yet has been done to allow the application of the gas engine in connection with electric generators of 7500 kw. or above.

3. The reciprocating steam engine still holds its own for small capacities, but for the capacities which we are here considering it has been superseded by the steam turbine.

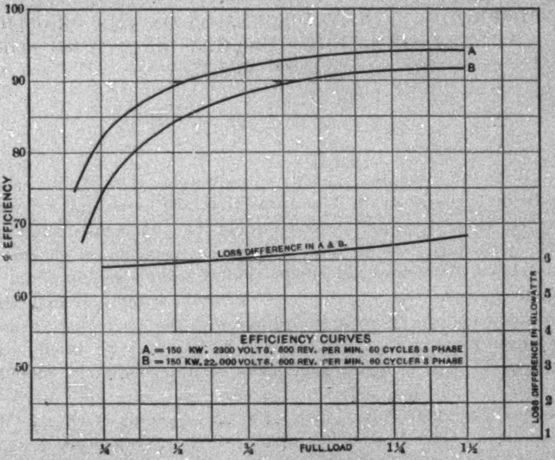

Fig. 1—Comparison of losses in high-voltage and loss-voltage generators.

4. The steam turbine in its present condition is pre-eminently adapted to large individual capacities. I should consider a steam turbine of 7500 kw. a comparatively small unit, and I am firmly of the conviction that steam turbines of 10 000 kw. or 15,000 kw., and even of 25,000 kw. will, before long, be developed and put into successful operation.

In thus looking to the steam turbine as the prime mover for generators of large capacity, we have limited our sphere of inquiry to generators of large capacity and high speed.

namely, conditions as best fitted for the operation of steam turbines. The question of high voltage in generators of small capacity and driven by other prime movers than the steam turbine will be referred to in the concluding paragraph.

STEAM-TURBINE GENERATORS FOR LARGE CAPACITY, 7500 KW. TO 15,000 KW. AND ABOVE

The difficulties encountered in winding generators for potentials of 20,000 volts or 25,000 volts are primarily mechanical difficulties. A coil containing a large number of small wires does not make a very mechanical piece of work. It would, therefore, appear to me desirable for the reasons here mentioned and some others, that the individual coils should consist of as few conductors as possible and that these conductors should be of such size as to enable the making of mechanically and electrically strong coils. Let us take a concrete example. A certain 7500 kw. turbo-generator wound for 11,000 volts and operating at 750 rev. per min. at 25 cycles, has six conductors per slot. A 7500 kw. generator wound for 22,000 volts, if designed along similar lines, would have twelve conductors per slot. Increasing the capacity of the generator from 7500 kw. to 15,000 kw. would enable the generator to be designed with six conductors per slot, and the difficulty produced by the higher voltage would be that of insulating the coils for the higher potential against ground. and against one another.

The insulation of the coils against ground is easier to obtain than against one another. The question of insulating the coils from one another is particularly difficult in turbo-generators on account of the crammed conditions of the winding space, but at the present state of the art it is possible to obtain the necessary insulation for 22,000 volts, although this can be done only with considerable expense. As soon as there will be a demand for large units wound for 22,000 volts, this demand will be met by machines carefully designed for these conditions.

The question of reliability of service is closely allied to that of quick repairs. It will be urged that not only is the danger of the breakdown of a 22,000-volt generator greater than that of a 11,000-volt generator, but also the repairs, consequent upon a breakdown, will be more difficult to make on the 22.000-volt generator. While this statement is perfectly true, a plan can readily be devised so as completely to defeat this argument. In a large power house in which a number of units of large capacity of the steam-turbine type are installed, the only rational way to make quick and satisfactory repairs consists in the carrying of spare parts. It will commend itself to the operators of power stations to carry a spare revolving field for one of these units and a complete set of spare armature coils. It must be insisted upon that the armature coils of these high-potential generators can readily be replaced, and, unless the machines are designed to permit this, it would be necessary even to carry a spare stator completely wound, which would be almost equivalent to having a spare unit in the power house.

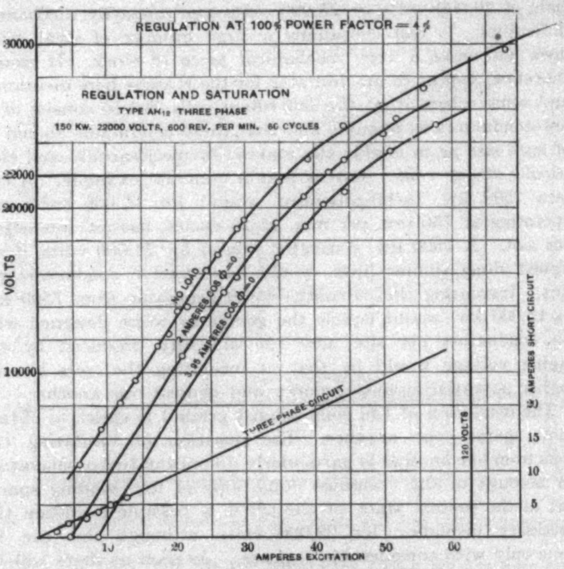

FIG. 2—Regulation curves of a 22,000-volt gaterator.

ECONOMY OBTAINED BY THE USE OF GENERATORS WOUND DIRECTLY FOR 20,000 VOLTS

The chief gains obtained by winding generators of large capacity directly for the high potential required for distribution consist in the simplification of the power plant and, probably, in a slightly reduced first cost. The question of reduced cost should certainly be considered a very minor factor, as reliability of service should be the criterion either in favor of, or against, the adoption of generators wound directly for high potential. Calculations of relative cost are here omitted on that account.

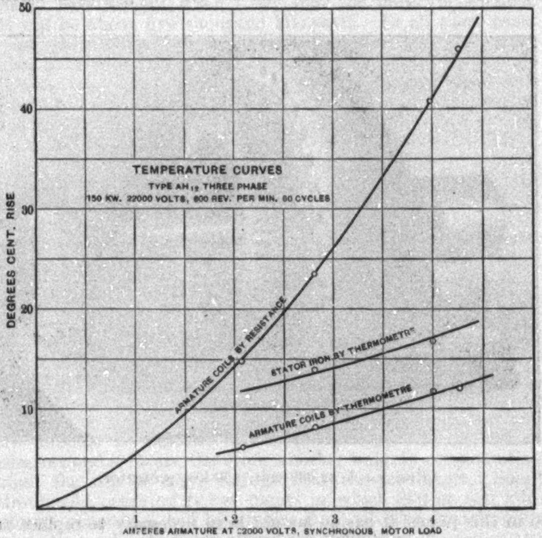

Fig. 3—Heating of armature coils.

Generators, Regardless of Size, for 20,000 Volts

For the sake of ascertaining the feasibility of insulating coils for 25,000 volts, the writer has had in operation a 150-kw. generator wound for 25,000 volts, 60 cycles, 600 rev. per min. This generator has been in operation for months, operating day and night under full load. Regulation curves and other data are illustrated in the accompanying diagrams. There is no doubt that there may be a limited field for units of small capacity wound for potentials above 11,000 volts, and the object of this paper is to call to the attention of the engineering profession the feasibility of generators of as small capacity as 150 kw., being wound for as high a potential as 25,000 volts. That the regulation, the heating, and the efficiency of this machine are very satisfactory is amply shown by the curves accompanying this paper. Should such machines be used in the future, it must always be insisted upon that the exchange of coils can readily be effected. In the 150-kw. generator referred to in this paper, it has so far not been necessary to replace any of the coils on account of defective insulation.

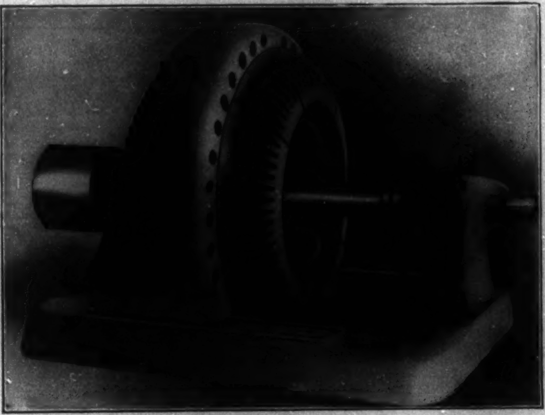

FIG. 4.—A 22,000-volt, 150-kw. generator.

SUMMARY

Where individual units of very large capacity are installed in power plants, a potential of 20,000 volts is feasible, and it is to be recommended in units of 10,000 kw. capacity and above.

Where individual units of small capacity are needed for a potential of 20,000 volts, the conditions can be met in most cases, even down to capacities of 150 kw.

DISCUSSION ON "THE PRACTICABILITY OF LARGE GENERATORS WOUND FOR 22,000 VOLTS," AT NEW YORK, MARCH 22, 1907.

B. A. Behrend: I stated that hydraulic turbines for large capacity, of 7500 kw. or above in individual units, are not likely to be of great importance at the present. The extensions at Niagara Falls may contain such large individual units; I hardly think that for the Victoria Falls of the Zambesi, units of 7500 kw. will be installed. Our chairman, Mr. Mershon, will probably bear me out when I say that the units for Victoria Falls will be about five thousand kilowatts. In all these cases the line potential will be high, and, therefore, the generators will not have to be wound for very high potentials. I believe, therefore, that my statement, that water-wheels need not seriously be considered as prime movers for large generators wound for high potential, is correct.

Let us take for example the system of the Interborough Rapid Transit Company of New York, in which generators wound for 11,000 volts are used; if the capacity of this system were larger and the area of distribution greater, 22,000 volts would have been seriously considered as the potential of the generators, rather than install units of 6600 volts or 11,000 volts transforming from this voltage to 22,000 volts. It must be distinctly understood that the potential of the generators is altogether dependent upon the conditions of the system of distribution.

I agree with Mr. Lincoln that reliability is more important than cost. To be able to keep a plant going is, in my opinion, the most important thing from the standpoint of the manufacturing and operating engineers. I want to call attention to the fact that repairs on high-speed generators are more difficult to make than on low-speed generators, as the coils are larger and more difficult to handle. This relates especially to turbo-generators and it forms, therefore, another weighty consideration against the use of high voltage in turbo-generators. Small hydraulically operated power plants in which 600 or 800 kilowatts are generated, will be simpler if no oil-filled transformers have to be used. As these plants are sometimes located in the mountains, this may be an advantage in certain cases. These generators are usually easy to repair, whereas repairs on oil-filled transformers take considerable time. Few power plants, therefore, care to depend upon repairs of transformers, but prefer to use a spare transformer. The 150-kw. generator which has been referred to in this paper was wound in two days, including the making of all connections. In Fig. 1 of this paper there are shown two efficiency curves, the one marked "*A*" referring to a 150-kw., 2200-volt, 600-rev. per min., 60-cycle, three-phase generator, and the other marked "*B*" referring to a 150-kw., 22,000-volt, 600-rev. per min. 60-cycle, three-phase generator. I have also plotted a curve which represents the difference in losses between "*A*" and "*B*". This loss corresponds to the loss in transformers used in connection with the 2200-volt generator, therefore, the efficiency of the high-voltage generator would be approximately equal to the efficiency of the low-voltage generator with the transformers. As far as I can see, the efficiencies are nearly the same in both cases. In Fig. 2 there will be found the regulation curves of the 22,000-volt generator, showing a regulation of 4 per cent. at a power-factor of 100 per cent. The temperature rise of the armature coils at 3.5 amperes is 16 or 17 degrees by resistance, and only 10 degrees by thermometer. I want to call particular attention to the difference in temperatures between the outside of the coil and the inside, so that, the temperature rise on the inside being, for instance, 60 degrees, the temperature on the outside might be only 30 degrees.

C. E. Skinner: The feasibility of using generators of 20,000 to 25,000 volts has been of very great interest to me for a number of years. In my opinion there are three main factors which must be considered in any discussion involving the use of these higher voltages directly on the generator: 1. cost of installation; 2, reliability of service; 3, performance of plant.

Cost of installation. I do not agree with Mr. Behrend that the question of cost can be left out of the discussion. I put the question of cost of first importance. Generators of 20,000 volts and above would hardly be considered at all for use in transmitting directly without the use of transformers unless there were some gain in cost. The decreased cost of such an installation of generators where 20,000 to 25,000 volts are used results from the omission of transformers, and some switchboard apparatus, and the requirement of less space for installation. Generators for a given output will be larger for the higher voltages, more lightning protection will be needed, and, according to Mr. Behrend's figures, a larger amount of money will be tied up in spare parts, particularly with relatively small plants. It is difficult, if not impossible, to make a general statement as to the relative cost of the two systems, as much depends on the size of units, the amount of power to be delivered, and the general requirements for handling the system. Without having made actual calculations, I believe that there are many cases where the cost of installation would be equal, if not greater, with high-voltage generators than with low-voltage generators and transformers where sufficient margin is allowed in spaces to insure the same reliability of service.

Assuming a plant of 10,000 kw. total, with generating units of 10,000 kw., the capacity of machinery installed would have to be double the output on account of requiring spare parts. If units of 5000 kw. are used, 50% must be added to the equipment. If the same plant is equipped with low-voltage generators and step-up transformers, it is my opinion that no spare generator would be required. If but one unit is used with three transformers in delta, it will be impossible, in case one transıormer breaks down, to operate without additional transformers—using two transformers in *V*. If the transformers are star-connected, one-third additional capacity in transformers would be required if a spare transformer is carried. Many plants operate year in and year out without spare transformers, and with much higher voltages than it is possible at the present time to use directly on the generators.

The constructional difficulties of high-voltage machines are much greater than with low-voltage machines and transformers. In a unit of any given size the number of conductors increases approximately in proportion to the voltage, and the cross-section of the conductor decreases inversely as the voltage. Armature coils are therefore mechanically much weaker, and, where the coil-throw is long—as in low-frequency machines, particularly low-frequency turbo-generators—the question of coil supports becomes more difficult as the voltage is increased.

Static and lightning troubles increase as the voltage increases; consequently, even for the same number of volts per turn, the insulation between turns must be greater with the higher voltages. The outer insulation increases approximately in proportion to the voltage. As a result the copper space in a given size of slot rapidly decreases and will eventually disappear. Very large slots are therefore necessary, and, to further the economy of insulation, the coils must be reduced to the lowest possible number.

Reliability of service. High-voltage machines are necessarily more subject to break down from all causes than are low-voltage generators; they are also harder to protect from lightning discharges of the same voltage. Repairs for the average machine are more difficult to make than for the average transformer of the same voltage. This feature has, no doubt, influenced Mr. Behrend in making the statement that it is necessary to carry complete spare parts for high-voltage generators.

The question of lightning protection is of great importance in any transmission system, and I believe the concensus of opinion among experienced engineers is that a generating station consisting of low-voltage generators with step-up transformers will be far easier to protect than a similar station using high-voltage generators, assuming the generator voltage to be between 20,000 and 30,000 volts. I have recently visited two stations using generating voltages between 20,000 and 30,000. The first has been in operation for some time, delivering power to the Valtellina Railway near Lecco, Italy. The generators are 20,000-volt, 3-phase, 15-cycle, direct connected to water wheels. That the lightning problem is a serious one at this station is proved by the fact that even though a large variety of lightning-arresters is installed, on several occasions the burning out of a generator has resulted from lightning discharges. At the time of my visit, additional types of lightning-arresters were in the station ready for installation in the hope that they would give relief from this difficulty. The second station referred to was not in operation; this is the Subiaco-Rome transmission, the generators being water-driven and the generating voltage 28,000. The whole installation including generators, switchboard, etc., is beautifully simple, but it remains to be seen whether this simplicity will exist after one or two seasons of operation.

Performance of plant. As before stated, high-voltage generators necessarily require open slots, the slots must be larger than those for low-voltage generators; and for economy of insulation the minimum number of coils must be used. This results in relatively high iron-losses and relatively poor regulation. At the present time there seems to be very little demand for 20,000- to 25,000-volt apparatus, except as additions to plants built some years ago.

Mr. Behrend says that steam turbines of 10,000 to 15,000 kw. and even 25,000 kw. will soon be developed and put into successful operation. There are already in operation a number of units which, while not rated at 10,000 kw. are, virtually of this capacity, and there are under construction steam-turbine units of 10,000 kw., with an overload guarantee. From 11,000- to 13,200-volt generators are in successful operation in this country; and one plant, the Los Angeles Edison Company, has been operating 7500-kw., 16,500-volt generators for some time.

I agree with Mr. Behrend that generators wound for voltages of from 20,000 to 25,000 are entirely feasible and that as soon as there is any real demand for such machines they can be successfully made. As before stated, it is chiefly a matter of cost, and it is also a question whether or not they are worth while. It is well known that a well-distributed winding gives better results both as to the performance of the generator itself and of other apparatus on the circuit, especially synchronous apparatus. The high-voltage generator plant is therefore at some disadvantage as compared with the low-voltage generator, step-up transformer plant in this regard. If large amounts of power are to be transmitted some distance, there will be used voltages higher than it is possible to use on generators at the present time. If for transmitting relatively small amounts of power within distances which can be reached by 20,000-volt transmission, the individual case must be considered. The cheapest outfit that will give equal reliability of service will, without doubt, be selected in every case. The use of such transmission plants would be limited to districts where large amounts of power are to be transmitted comparatively short distances; for instance, for railway service in large cities such as the present system installed in New York City, this being at the present time 11,000 volts. Increasing this voltage of 11,000 to 25,000, involves the subject of cables, etc., and requires very careful working out in order to determine whether or not there would be real economy in the increased voltage. For transmitting smaller amounts of power to greater distances, it is my opinion that the most popular method for some time to come will be the low-voltage generator with step-up transformers.

In regard to possible size of steam turbines, I think that units of 25,000 kw. are even now within reach. The steamships Lusitania and Moritania, now building on the river Clyde, will have steam turbines as their motive power, the turbine units to be something like 30,000 h.p. If such machines can be built for steamship service, they are, of course, available for the driving of electric generators, and generators of this capacity will without doubt be developed commercially as soon as there is a real need for them.

W. S. Murray: In matters of this kind cost must ever enter as an important factor. Though it may be possible, by a combination of the generators and transformers, to equip a generating plant for the same money as that required to pay for generators without transformers, yet it seems to me that such a combination should not be considered until necessity makes its development imperative. Also, there is no doubt but that in creating high voltages in a generating apparatus, the active conductors of which are limited to a few coils, there is also created very poor regulation. High-voltage apparatus will therefore drive the designer from well-distributed windings to coil-wound armatures.

I wish to support Mr. Skinner's statement in regard to the protection of the station by means of transformers. If there are great transmission distances, naturally the voltage has to be increased, and under these conditions there is no better lightning protection than well-designed step-up transformers.

Though Mr. Behrend contends that the repairs on transformers are rather difficult to make, still it should not be forgotten that the cost of equipping a step-up station with spare transformers is much less than that of equipping a station with spare generators.

My conception of a well-designed high-voltage power house—by high voltage I mean 20,000 volts or more—is that of a fort, the ramparts of which are the transformers; they take most of the hard blows. It is not necessary to compare the damage by lightning in a plant having transformers between the generator and the line with a plant that is not equipped in this way.

In view of the fact that the generator-transformer combination affords better lightning protection, I admit that I shall remain heartily in favor of step-up apparatus until a real case is made out for high-voltage machines.

A. H. Armstrong: The design of any type of apparatus must be governed by commercial demands. Generating and transmitting systems may be divided into two broad classes; those centering in and about large cities and operating at from 6,000 to 11,000 volts, and those having an unlimited area of distribution calling for potentials of 33,000 volts, 44,000 volts, or higher.

Mr. Behrend would have us believe that the choice of transmission potentials is dictated by the limitations of generator design and that the installation of 5,000 and 10,000 units offers the opportunity for higher generator potentials, and hence permits the adoption of higher distributing potentials in and about cities. I cannot take this view of the matter, as the potential of city distributing systems is limited by other considerations than those of machine design. To substantiate this statement I would point out that the generators with highest voltages are not the large units used in city generating stations but the smaller units used in interurban railway and general power distribution systems. The manufacturers are perfectly willing and able to build generators for higher potentials than 11,000 volts, but the fact that low potentials are still adhered to in city distributing systems bears out my statement that the potential of such a system is dictated by questions of reliability of cable distribution and the general needs of the distributing system rather than by any inability or unwillingness of manufacturers to construct machines for 15,000 or 20,000 volts.

While generators may be wound for 15,000 to 20,000 volts, these potentials fall far short of the requirements of a general distributing system outside of large cities. The history of such distributing systems indicates a tendency towards large generating stations feeding over considerable areas at the highest practicable potential; and the potentials required are so much in excess of what can be accomplished in generator design that it would seem, considering the transmission problem broadly, that the low-potential generator used in connection with step-up transformers must continue to be considered the best engineering.

Furthermore, both railway and general transmission systems are constantly expanding over increased areas, and the history of such systems has been to call for a much higher potential than that adopted in the original installation. The flexibility provided by low-voltage generators and step-up transformers takes care of the needs of the expanding system, while it is very probable that a high-voltage generator wound for the original transmission potential would ultimately be used in connection with step-up transformers.

W. L. Waters: The best answer to an inquiry as to the practicability of large alternators wound for 20,000 volts is that such alternators have already been built and are in operation. I would modify somewhat the history of high-voltage alternators from that given by Mr. Behrend. The first high-voltage alternators were the 10,000-volt, 1000-kw. Deptford alternators built by Ferranti in 1889. Then in 1897 came the 15,000-volt, 1800-kw. Paderno alternators built by Brown Boveri, and then in 1900 came the 20,000-volt, 1050-kw. alternators built by Schuckert for the Valtellina line.

The practicability of building high-voltage alternators depends entirely on the nature of the workmanship put into them.

The design of such alternators is similar to that of 6600-volt alternators; the only point for the designer to take care of is to make the work on the armature winding as easy as possible for the shop. After this is done, it is altogether a question of careful and skilful work in the armature-winding department. The larger the output of the alternator the easier it is to make a satisfactory high-voltage armature coil, as the conductors per slot are fewer and they are of larger section and consequently more rigid. It is only with alternators of small ampere capacity that serious difficulties arise.

Mr. Behrend mentions a 150-kw. 22,000-volt alternator which has been in operation for sometime. Mr. Behrend is not particularly specific as to the conditions of load under which this machine has been operated. As far as can be seen from the paper, this machine was operated under a steady synchronous motor load. This is not nearly so severe a test as that where an alternator is continually subjected to sudden variations in load, heating and cooling, being taken off and thrown on the line, and possibly short-circuits. It is quite possible that Mr. Behrend would have a different experience with that alternator if it were operated in some small power station on a high-voltage line.

Breakdowns of the insulation to ground or between phases rarely happens. On high-voltage alternators, breakdowns virtually always start as short-circuits between the individual turns of a coil. In regard to their liability to such short-circuits between conductors in the same coil, it is my experience that there is very little difference between 6000-volt alternators and those of higher voltage. These short-circuits are apparently caused partly by sudden surges on the line, and partly by the gradual deterioration of the insulation due to the vibration of the individual conductors in the coil. This gives as a first requisite of a high-voltage alternator, that it must have the insulation on each conductor as good and as permanent and as strong mechanically as possible, and that the conductors must be held perfectly rigid both in the slot and outside. This practically means the abandonment of the scheme of threading the conductors through a closed insulating tube. Though this construction has been standard in Europe for high-voltage work, and has been used to a certain extent in this country, I think we shall find that it will gradually be abandoned in favor of the form-wound and subsequently insulated coil for all high-voltage work. It is almost impossible to make a perfect high-voltage coil out of small wires, such as would be used on a 150-kw. 22,000-volt machine, as such a coil could not very well be made sufficiently rigid to last any length of time. For this reason I think that about 30 amperes is the minimum current capacity for which high-voltage alternators can be constructed; with very careful shop work, 30-ampere alternators can be constructed up to 30,000 volts. With steam-turbine alternators there are liable to be extra difficulties on account of crowded space available for the end-connections, but this crowded space is chiefly due to the demand for small floor space for these alternators, and extra space will probably have to be allowed for 25,000-volt machines. If this were done, there would be no more difficulty with a steam-turbine alternator than with any other alternator of like capacity.

The demand for such high-voltage alternators would practically be limited to systems operating with 20,000-volt lines. If such a system were of comparatively small capacity and operating on overhead lines, 20,000-volt generators would hardly be desirable, as the supervision would probably not be of the best and the danger of operating directly on a overhead line would be too great on account of possible lightning troubles, so that probably in this case the usual system of a low-voltage generator with transformers would be used. For large city power system work, there would be undoubtedly a certain demand for such generators, especially as 20,000-volt cables are now in use. In such a case, a 20-000,volt generator would be somewhat simpler than a low-voltage generator and transformers, and probably somewhat cheaper. If a demand for such 20,000-volt alternators does arise, I think that they can undoubtedly be manufactured to operate as reliably as 6000- and 12,000-volt machines.

H. G. Stott: Mr. Behrend's able and suggestive paper upon the characteristics of high-tension generators raises the point for discussion of whether we need them or not. I believe that the ultimate solution of this matter lies, not in the generator, but in the question of how far we dare go in voltage in underground cables.

With high-tension transmission, oil-cooled transformers are now invariably installed in all cases where the voltage is above 20,000, as the advantages to be gained by the oil acting as insulation are now fully recognized by all.

The transformer as a piece of lightning protective apparatus is a most important consideration, as very few cases are on record of generators being injured by lightning when transformers were interposed between them and the line. If a transformer were destroyed by lightning, it could be cut out in a few minutes, whereas if a generator were struck, the repairs to it would cover several days.

Professor Ryan's classical paper, read before the Institute two years ago*, showed that owing to the concentration of electrostatic stress on a conductor, there was a limiting diameter of copper for each voltage, below which it is not safe to go; so that unless very large quantities of power are to be transmitted, nothing is gained by increasing the generator voltage.

The limit of generator voltage would thus seem to be determined by considerations entirely outside of the machine itself.

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* "The Conductivity of the Atmosphere at High Voltages," by Harris J. Ryan. TRANSACTIONS A. I. E. E., 1904. Vol. XXIII, p. 101.

Percy H. Thomas: The practicability of 22,000-volt generators must evidently depend largely upon their capacity and also upon the speed and other features of the design which will be determined by the conditions of the plant. What can readily be done in generators of the size and type of those in the Interborough Rapid Transit Company's 59th street power house, is hardly practicable in a small generator requiring fine wire windings.

Although the high-tension generator eliminates transformers and some switches, and perhaps switchboards, it has the disadvantage in parallel operation that all high-tension lines must be electrically connected; whereas with low-voltage generators and step-up transformers, paralleling may be done on the low-tension bus-bars, thus electrically disconnecting the high-tension circuits from one another where found convenient.

The importance of this point must not be overlooked. Further experience with large high-tension systems will probably demonstrate that a material increase in reliability of operation will be obtained by maintaining electrically separate the naturally separate divisions of the transmission system. For example, where power is transmitted over different routes to the same sub-station, or to an entirely different sub-station, no limitation of capacity will result by paralleling on the low-tension, if as is usual the capacity of a single line is equal to that of one or more groups of transformers. By this arrangement, the direct effect of lightning discharges, grounds, and short-circuits occurring in one of the separate lines is practically nothing on the others; with the present frequent paralleling of the whole system on the high-tension, however, each high-tension disturbance of a severe character equally endangers virtually all of the transmission system.

A good example of the seriousness of this condition is the accident and shutdown described by Dr. Steinmetz before the Asheville Convention, in 1905. In this case a large electrical railway plant operating all its high-tension apparatus from a common bus-bar was shut down for a considerable length of time by several simultaneous failures of cables and other apparatus, presumably all resulting from a single break. This system had high-tension generators; had it been supplied with low-potential machines and step-up transformers and had each sub-station been operating independently on its high-tension lines, or had it been otherwise possible to obtain this electrical independence, it is very likely that this breakdown would have involved only the sub-station in which the original break occurred, leaving the road perfectly able to operate its entire system. I do not mean to express the opinion that under all conditions this is sufficient reason for foregoing all the advantages of high-tension multiple operation or high-tension generators, but simply to say that I believe this condition must be taken into account and that actual experience with high-tension plants is such that it should receive considerable weight.

The matter of insulation must receive the most careful attention in high-voltage generators, not only insulation between windings and core and between overlapping coils of different potential, but between turns of windings especially near the leads. The concentration of potential on the outer turns of a transformer connected to a line subject to "static" is well known. This same condition must, of course, exist in a high-tension generator connected to such a line, and in most cases substantial protection or sufficient insulation between turns is much more difficult to obtain. For instance, the peculiar shapes of the armature coils found necessary for mechanical reasons, renders it difficult to get the high insulation strength between adjacent wires or layers. In view of the inductance of these coils and the capacity of the windings of the core, there will always be a strong tendency for static disturbances to pass between turns in such coils. The chances that such static puncture will result in a short circuit supported by the generator electromotive force are exceptionally good. It is often said that additional insulation may be used in the coils nearest the line to meet this danger; this method is generally impracticable, however, since the increase in strain upon these coils is not of a reasonable magnitude, say two or three times, but may be ten or twenty times the normal strain. The conditions rapidly become more severe as the voltage rises. Personally, I believe that usually on the higher voltage machines the only practicable solution is in protective apparatus. As a matter of actual experience, the short-circuit of coils of high-tension generators connected to lines, except in favorable conditions, such as are often found in very large 10,000 generators, is a serious handicap.

On the other hand, it is usually found that the numerical constants, involving the number of turns and exposed surface of the coil, are such that a choke-coil will be much more effective in protecting a high-tension generator than it will in protecting a high-tension transformer. In many cases it is likely that a static interrupter will be found more economical in space and cost than an equally powerful choke-coil.

It is an unfortunate fact, borne out by examples in actual service, that the short-circuiting of an end-coil in a high-tension generator operating on a transmission line throws the original strain, possibly only slightly reduced in intensity, directly upon the second coil, which will then often break down, and the third coil will in turn be subjected to similar conditions, etc. I have in mind one case where such a discharge passed across coils all the way from one generator lead to another, the marks being traceable in nearly all the coils. In many cases there were pittings of the wires showing the following of current sustained by the generator.

I wish to urge strongly the importance of protecting against the unusual susceptibility of a high-tension generator to short-circuits between turns of the end-coils, when subjected to static strains. A single breakdown in a generator disables the whole machine, whereas one of a group of three transformers in delta may be spared without serious inconvenience.

Philip Torchio: Not long ago I happened to deal with a large water-power proposition in which the conditions seemed to warrant the use of 22,000-volt generators, as the total length of the transmission line was about 15 miles, with a total capacity of 30,000 to 40,000 kilowatts. Manufacturers were asked to make a preliminary study for machines of 2250 kw. 25,000 volts, 3-phase, 60-cycle, 112.5 rev. per min. Under these specific conditions it was found that the costs and efficiencies of generators of different voltages would be approximately as follows:

Voltage of alternator	Relative cost	Relative efficiency
2,300	100%	96%
15,000	130%	95.25
25,000	155%	94.20

From the above it would appear that as far as cost and efficiency are concerned, there would be hardly any difference between the low-voltage generator with step-up transformer and the 25,000-volt generator. On the other hand, if step-up transformers are used, great savings can be made in the copper and transmission line by raising the voltage higher, say. to 44,000 volts, which can now be made as entirely safe to operate as the lower voltage, and probably, in connection with oil transformers, safer than with 25,000-volt generators.

The selection of generator voltages is usually determined by the conditions of distribution Lighting companies have usually been conservative and seldom exceeded 6600–9000 volts. Electric railroads, on the other hand, have adopted 11,000–13,000 volts, but in most instances the extra insulation on cables has almost entirely offset the reduction in their copper cross-section. I think, however, that with proper grading of insulation on cables, one can now get greater economy from higher voltages then have been heretofore realized

Aside from these considerations, if we are unhampered by any restriction, the problem of selection of voltage simmers down to the question of cost of cable wiring and switch-gear at the station, as with large generating units the problem becomes rather troublesome if great amounts of current are to be handled in the station One will readily appreciate these difficulties if he considers that a 20,000-kw. generator with 50 per cent. overload would require switches of about 8,000 amperes' capacity at 2,200 volts. If, however, 12,000 volts are used, 1500-ampere switches can be substituted with the overall dimensions practically unchanged. If the voltage should be doubled the current would be halved, but the difficulties and costs would be greatly increased in getting the proper insulation on cables and the proper spacing of the high-tension switch elements.

Offhand, I would say that in large central stations these considerations would prohibit the use of high-voltage generators. The above applies to large units.

In the case of smaller units I should think the conditions would not materially change the above conclusions.

In connection with high-voltage generators, it may be interesting to mention the fact that Italy was among the first to use high-voltage generators with their water power transmission plants. The Paderno installation was designed between 1895 and 1896, using 2,200-h.p. Brown Boveri units wound for 15,000 volts. Later the Valtelina three-phase railway installed three 1,500-kw., 22,000-volt, 3-phase, 15-cycle, 150-rev. per min. Ganz generators, wound for star connection and tunnel winding. This and other plants have been operated for many years, and I believe that were it not for the difficulties of installation inherent to the type of slot, the service would have been considered satisfactory. With this type of winding the greatest drawback is the length of time that is required to replace a burned out coil. The explanation for the favor of high-voltage generators in Italy lies, in my opinion, in the fact of the relatively short length of transmission lines and the multiplicity of distributing lines, making desirable the use of a moderately high voltage, which happened to be very close to the commercial dividing line between direct-wound generators and generators with step-up transformers.

F. V. Henshaw: In connection with high-voltage, air-cooled transformers, will Mr. Torchio say if he has any information of any case of deterioration of the insulation due to ozone, or chemical action resulting from brush discharge.

Philip Torchio: With a certain type of coil, insulated in a certain manner, from experience with moderately high voltages covering a great number of units operated for many years without breakdowns of any kind except due to mechanical injury, I would take my chances with 20,000-volt coils; I would not bother about the ozone. With some other insulation, I would not take chances with 2200 volts.

C. F. Scott: I have just made some general calculations to determine the field of application for generators of 150 kw., wound for 25,000 volts. The distance of transmission will ordinarily exceed 25 miles, as a less distance would not necessitate so high a voltage. If No. 6 wire be assumed as the smallest convenient practical line wire, we will find that the cost of the transmission line will approximate, say, $25,000. It is desirable, therefore, that such a line transmit considerably more than 150 kw. in order that the cost of the line per kilowatt will be small. Moreover, such a line will transmit 150 kw. with a loss of only about one per cent. Such a line, therefore, has a capacity for transmitting 1,000 kw, or 1,500 kw., and, if this amount of power is to be generated and transmitted, it will usually be advantageous to use a few large machines instead of many small ones. In other words, 150 kw. is too small a unit for the generation of power at 25,000 volts. The application of generators of this kind, as has already been pointed out, would be quite special.

Paul M. Lincoln: What capacity would the generator have if wound for 2200 volts instead of for 22,000 volts, with a regulation of from say, eight to ten per cent?

I agree with Mr. Stott that the oil used in transformers is of great advantage, and enhances the desirability of the transformer combination over the high-voltage generator. Oil has the property of automatically healing insulation ruptures, and for that reason I believe that such a combination would be much freer from lightning troubles than would a high-voltage generator. Another thing that operates against the high-voltage generator, particularly one of good regulation, such as the one mentioned in the paper, is the liability of the winding to bend on sudden short-circuits. The reasons for this are two: first, on account of the turns being many and the wire therefore necessarily thin and weak; secondly, the good regulation causes a much larger rush of current on such a short-circuit, thereby making the bending forces the greater.

B. A. Behrend: I think that my commentators are laboring under the impression that I had chosen the title of this paper for the purpose of advocating broadly the use of 22,000-volt generators for all sorts of purposes. Let me say, therefore, that the subject of this paper was assigned to me by the chairman of the high-tension Transmission Committee, who, knowing perhaps that I am something of a wolf in the fold and might start some discussion, suggested the title of this paper.

Mr Skinner is well known for his good work on insulation, but I confess that I should have relished Mr. Skinner's remarks better if he had, for the time being, forgotten that we are not connected with the same business interests.

Turning, now, to the technical statements in Mr. Skinner's remarks I must say that I really concur with him in everything he has said except the mode in which it was put. Regarding the point already raised by Mr. Mershon and brought up by Mr. Skinner, concerning the relative cost of the apparatus in question, Mr. Torchio has cited an interesting case. Mr. Mershon requested me to give a comparison of prices and, therefore, I sent an inquiry to our sales department with the following result. A 200-kw., 2200-volt 3-phase, 600-rev. per min. generator with three 75-kw., 2200-volt to 22,000-volt. transformers would be sold for $3,849.00. A 200-kw., 22,000-volt, 3-phase, 600 rev. per min. generator would be sold for $3,837.00; the difference is only $12.00 between the two plants. The total shipping weight of the 22,000-volt generator is 31,000 lb., whereas the shipping weight of the combination of generator and transformers is 30,650 lb. Freight charges, therefore, would not seriously interfere with the sale of these machines in far-off districts.

Mr. Skinner and other gentlemen have imputed to me the statement that the voltage of the generator should determine the line voltage; what I did say was that it was the external conditions, the amount of power to be distributed, the area of distribution, and other conditions that determine the line voltage. If the line voltage thus determined happens to be such that the generators can readily be wound for it, the omission of the transformers may seriously be considered.

Mr Skinner referred to the question of money tied up in spare parts. I can argue on this only academically but, as this paper has been written for the purpose of " raising the dust "—in the laying of which we are concerned in this discussion—I may as well raise some more dust. I stated that the carrying of spare parts and the repairing of the generators was a comparatively inexpensive and simple matter. If a single coil breaks down, a repair can often be quickly made by bridging over and cutting out the injured coil. In a small power plant the carrying of a few spare coils is no worse than the carrying of a spare transformer.

I distinctly said, in reading my paper, that 20,000 volts need not be used for distribution in a city of the size of New York; the amount of power and the area of distribution are not great enough. The population of New York will have to be increased before 20,000 volts will be needed on our generators! 11,000 volts is perfectly satisfactory for the area that has to be covered in this city. At the present time, there are no cities large enough in this country to justify a higher potential. But twenty-five years hence the population of New York will be at least doubled, and then the problems which we are now discussing in an academic way will have become actual problems, unless a widely different system should be discovered or invented.

Mr. Murray agreed with Mr. Skinner so thoroughly that I need not reply in detail to his remarks. But I want to say one word or two about a statement that he made three times: he called the 22,000-volt machine, to which I have referred in my paper, " a very very poor piece of regulating apparatus ". So, then, 4 per cent. regulation is " very very poor "! Four per cent. regulation can not be got at all with transformers and low-voltage alternators designed for 8 or 10 per cent. regulation!

Mr. Armstrong said that " Mr. Behrend wants us to believe " that generators should be wound for 22,000 volts and that this voltage, therefore, should be used for distribution and as line potential. And then he proceeded to show that this statement, which I have never made, is absolutely wrong. I referred, while reading my paper, to the power plant in which Mr. Mershon is interested at Victoria Falls of the Zambesi River. The distance from Victoria Falls to the South African mining district is about 600 or 700 miles. The transmission line will be operated at a potential of 100,000 volts or more, and it goes over the heads of Kaffirs and lions, and one certainly would not select generators of 22,000 volts for this transmission line. I thought that I was speaking to experienced electrical engineers who were fully conversant with all these conditions, and I thought that Mr. Armstrong would hardly be misled to believe that the potential of the generators determined the line potential. But I also stated that the conditions external to the power plant determined the choice of the voltage of the generators. A competent engineer must be able to see more than merely the generating plant; he must have a grasp of the conditions of the entire system, including the transmission line and the conditions of distribution and utilization, as these determine the choice of the line voltage and the voltage of the generators.

I heartily endorse Mr. Waters' remarks. Good shop work must be put into high-voltage machines, and there is no use in denying the fact that it is difficult to obtain thoroughly reliable workmen to whom such work can be safely entrusted. Here lies one of the chief difficulties connected with the building of high-potential generators. Mr. Waters is right that good workmanship on high voltage coils is of the utmost importance.

Mr. Stott's remarks contain statements which I should have included in my paper. He emphasized the fact that the insulation of the cables at present forms one of the chief obstacles to an increase in the generator voltage in large power plants. I am completely in accord with Mr. Stott in regard to the great advantage obtained from oil used as an insulator. It has been proposed to use oil for insulating the stator of electric generators for high potential. This appears feasible but, at the present time, I should prefer to instruct our sales department to quote rather high prices on such oil-insulated generators.

Some one has asked about the wave shape of the generator described in this paper. I have not yet had an opportunity to determine the wave shape by means of an oscillograph, but I hope to do so later. The generator which was used for 22,000 volts was a stock machine having the same number of slots as that used for potentials varying from 10,000 to 15,000 volts. There are many machines of this type and size in operation both as generators and as synchronous motors, operating on short and long lines, and there has never been the least trouble with these machines and certainly no trouble due to wave shape.

It was stated that the manufacturer preferred to sell the generator and the transformers rather than the high-potential generator by itself. This point was also raised by our sales department; they were afraid that they would be overrun with orders for 22,000-volt generators, but I assured them they would get none.

Mr. Thomas made some most interesting remarks on the subject of lightning protection, as might be expected from this thoughtful source. I well remember how he called attention several years ago, in his excellent paper before this Institute, to the fact that the strain increases between the end layers of a transformer coil, and, of course, it does likewise in the coils of alternators and synchronous motors. In the discussion of Mr. Thomas' paper,* I showed mathematically and graphically, by the use of Fourier's analysis, this increase in strain—and I want to say, in this connection, that we are always careful in the insulating of our coils to look out for the stresses between layers—I believe that it is quite feasible to insulate individual conductors in the coils closest to the terminals in such a manner that a breakdown from this source is not likely to occur. Mr. Thomas also called attention to the use of choke-coils in connection with lightning protection. Mr. Thomas knows a great deal more about lightning protection than I do, yet I wish to state that in Switzerland and northern Italy, where plants located in the mountains are subjected to considerable danger from lightning, insulation of the frame of the generator is resorted to as a means of lightning protection. Generators and motors are mounted on porcelain insulators and, while this may not appear a very mechanical construction, it has proved an excellent protection against lightning.

Mr. Torchio has stated a case of 2,200-kw. generators wound for 22,000 volts, on the one hand, and wound for 22,000 volts with transformers on the other, and he has remarked that the prices which have been quoted him by different manufacturers for these different types of plant were almost exactly the same. This bears out the statement made by me in this discussion, that there is but little difference in the relative cost of high-voltage generators, and of low-voltage generators and transformers. Mr. Torchio has also called attention to the difficulties at present connected with the use of high-potential cables. I am in thorough accord with what he has said on this subject.

Mr. Scott has asked me where such machines would be used. I have said in this discussion that there are a number of small plants of 300 or 500 kw., in which 22,000 volts would be a satisfactory line potential and, in this case, by winding the generators for 22,000 volts, a considerable simplification of the power house may be obtained. There is also little force to the argument that the manufacturers will refuse to build 22,000-volt machines, as they are special. We actually took a standard 12,000-volt machine, and wound it for 22,000 volts.

I am in accord with Mr. Scott in regard to his statement that some engineers recommend the same system under all sorts of conditions. There is no panacea for all the troubles that are encountered in our work, and I am glad to find Mr. Scott among those who advocate the taking of a broad view, though I fear that Mr. Scott and all the rest of us will be in our graves when engineers are still persisting in advocating a specific system for all conditions.

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* Static Strains in High-Tension Circuits, and the Protection of Apparatus," by Percy H. Thomas. TRANSACTIONS A. I. E. E., 1902. Vol. XIX, pp. 213–276.

W. S. Murray: Does Mr. Behrend really mean that on the high-voltage machine, notwithstanding the fact that the distributed winding must be dispensed with, that the regulation will be as good? If conductors are bunched will there not be a much larger percentage in regulation? Is Mr. Behrend willing to say that he expects this regulation to be just as good without the distributed winding? Regulation is one of the most important things in the design of large transmission plants, and it cannot possibly be overlooked.

B. A. Behrend: In answering Mr. Murray's question, I should like to state the facts. Comparing with one another, a generator having one slot per pole per phase, a generator having two slots per pole per phase, a generator having three slots per pole per phase, a generator having five or six slots per pole per phase—all cases with which I am thoroughly familiar through my own personal experience in designing some million or more kilowatts of such generators—I must state that I have been unable to notice, in spite of most carefully carried on experiments, any appreciable difference in the regulation of these machines. There ought to be, and there probably is, a slight difference in the regulation, but it is too slight to be established with certainty. The armature reaction is less in the generator having few slots, while the self-induction caused by local fields in the armature winding is greater. Thus, the theory of armature reaction shows that below saturation there is no difference in the regulation, while at high saturation there is a slight difference in favor of the machine having many slots. We have a number of generators and synchronous motors operating in parallel with different numbers of slots per pole per phase, and certainly no difficulty has ever been experienced on that score.

W. S. Murray: I understand that it is not entirely a question of self-induction—it is the result of the two. Does Mr. Behrend feel that his remark—that his conclusion—is applicable to very large units and also generators wound for single-phase transmission? That is that 20,000-volt generators will give as good regulation as distributed-wound generators?

B. A. Behrend: To answer Mr. Murray's question I would say that the regulation is practically the same in both cases, understanding by regulation the voltage drop between no load and full load. I have had no experience with single-phase railway work, but I should say that it will be necessary to avail oneself of all possible advantages by designing a generator so as to give as nearly a sine curve as possible, so as to make it as easy as possible for the single-phase motors. Advantage should be taken of everything to make it easier for the single-phase motors.

W. S. Murray: Does the remark of 4% regulation apply?

B. A. Behrend: There should, of course, be good regulation in a single-phase railway plant on account of the large wattless currents. But this regulation depends rather on other factors, as the reluctance of the magnetic circuit, the amount of excitation, than on the number of slots per pole per phase.

Ralph D. Mershon: I hope that Mr. Behrend later on will give us some cost and efficiency figures for such generators as compared with lower voltage generators combined with transformers, as I believe he has such figures at hand.

I was rather surprised to hear Mr. Skinner lay so much stress upon the question of lightning protection. From what I know of his attitude relating to choke-coils, I should have expected him to assume that enough choke-coils would be used in series with the generators to protect them. Contrary to Mr. Stott's experience, I have known of several cases where generators having step-up transformers between them and the line were damaged by reason of lightning discharges. I have known such trouble to occur without any apparent damage to the transformer. In such cases the static discharge which damaged the generator was probably induced in the low-voltage circuit of the transformers by the electrostatic inductive action between the windings of the transformers. In some cases, however, there may have been a break down between the high- and low-voltage windings of the transformers which breakdown repaired itself by reason of the healing action of the transformer oil. I think there is, unquestionably, a place for the high-voltage generator, and this paper of Mr. Behrend's is very timely. I have listened to it with a very great deal of interest indeed, and will receive with even more interest the cost and efficiency figures previously mentioned which I understand he will give us later on.

F. G. Baum (by letter): I take exception to the statement that hydraulic units of or above 7,500 kw. are not to be considered of importance at present. Several installations are under way for hydraulic units of 7,500 and 10,000 kw., and by putting a turbine on each end of the generator shaft, there may be produced units as large as 15,000 kw., or even 20,000 kw.

The disadvantages of winding for a high voltage are:

1. Increased losses.
2. Increased cost.
3. Decreased capacity.
4. Increased danger and risk of breakdown.

The advantage is that reduced space is required, as no transformers are necessary.

In some localities the question would be answered by the cost of space, but, eliminating the space-factor, it does not seem advisable to wind for 22,000 volts. At some point it is folly to increase the voltage on generators. I am inclined to the opinion that this folly point is reached in most cases before 22,000 volts is attained.

Ernst J. Berg (by letter): I quite agree with Mr. Behrend that large turbo-generators lend themselves best to very high voltage windings. At the same time it may be of interest to know that one manufacturing company has built 18,000-volt alternators directly connected to slow-speed engines.

The transmission line voltage has, in my opinion, a bearing on the best generator voltage, since with one of the high-potential lines grounded in a delta system, high static stresses are induced in the generator windings. These do indeed occur even in a grounded star system when power is conveyed over two of the lines and the ground used as a third conductor.

Therefore, it is evident that it is not well to make the generator voltage too low in reference to the line voltage. My judgment would be that it ought to be not less than one-sixth or one-fourth of the line voltage, corresponding to 16,000–25,000 volts in a 100,000-volt transmission system. Judging from the amount of insulation required in transformers, the limit would seem to lie somewhere between 20,000 to 25,000 volts, provided alternators of reasonable wave shapes are demanded.

W. J. Foster (by letter): The question of practicability involves construction cost and efficiency. It may be said that the question of construction is wholly one of insulation. Is it possible to allow the space necessary for the insulation and so to apply it as to insure against breakdowns? This may be answered in the affirmative, with the qualification that large slots are always possible where the pole-pitch is large. Hence, there are certain sizes of generators that are well adapted for such high potentials. It is probable that the simplest way of putting this matter above a certain minimum size is to make the output per pole the criterion, since this eliminates to some extent the consideration of periodicity. It is probable that almost any generator with a capacity of 1000 kw., or more, whose output per pole is at least 100 kw., can be advantageously wound for 22,000 volts. All steam-turbine generators up to 60 cycles belong in this class. There is another type of generator that is admirably adapted to 22,000 volts; namely, the large engine-driven fly-wheel type. Such generators have a large pole pitch, and, consequently, make it possible to select the number of slots that permit of the necessary room for insulation between winding and core. They also make the high-potential machine desirable by reason of the fact that a large percentage of their cost is due to the mechanical parts. Hence the additional cost of the high-potential machine is generally less than the cost of step-up transformers. It is frequently much less. Furthermore, the efficiency of such a generator is much higher than the combined efficiency of the low-potential generator with step-up transformers.

The synchronous motor in motor-generator sets and frequency-changer sets in sizes of 1000 kw. or more, may often most advantageously be wound for 20,000 volts. The majority of these are for low frequency, such as 25 cycles, and for use in sub-stations to drive direct-current generators or alternating-current 60-cycle generators. Winding for 20,000 volts will frequently simplify the sub-station by eliminating step-down transformers;

at the same time it will invariably increase the efficiency of the transformation.

I wish briefly to describe some 5000-kw., 50-cycle, 100-rev. per min. engine-driven, fly-wheel type generators that have been constructed to operate at approximately 20,000 volts, three-phase. The ampere rating of these generators corresponds to a normal potential of 18,000 volts, but the specifications require them to be capable of operating at a maximum of 22,000 volts. Three of these generators are being installed in the plant of the Pacific Light and Power Co., Los Angeles, California.

Floor space required	31 ft by 6 ft. 9 in.
Diameter of stator	28.5 ft.
Diameter of rotor	25 ft.
Radius of gyration	8.8 ft.
Weight of rotor	186,000 lb.
Weight of stator	162,000 "
Weight of accessories	12,000 "
Total weight	360,000 "

The armature coils have stood a high-potential test of 40,000 volts for one minute.

The commercial efficiency is as follows:

1.25 load	96.5%
Full load	96.2%
0.75 "	95.2%
0.50 "	93.5%
0.25 "	88.0%

The class of generators which will undoubtedly make the best showing in the matter of cost to the customer is the large fly-wheel type of low periodicity, such, for instance, as a 25-cycle, 5000 kw., 75 rev. per min. Such a generator wound for 22,000 volts, will not cost the customer more than 15% above the cost of the generator wound for the most advantageous potential with step-up transformers. Step-up transformers will cost about 30% of that of the generator. Hence there is a saving in the initial cost of the apparatus alone of from 10 to 15%. To this should be added the saving in the station due to the elimination of space for transformers. Along with this saving in the initial cost there will accrue to the consumer a continual revenue due to the better efficiency. This will amount to at least 1% at full load and 1.5% at one-half load. Many large water-wheel driven generators might well be wound for 22,000 volts where it is desirable to use that potential on the transmission lines. It would be an interesting study to work out the cost and efficiency of such generators for transmitting Niagara power to Buffalo in comparison with the use of generators with step-up transformers, as at present. There is no doubt in my mind but that a most decided gain would be shown. The 3750-kw. generators on the American side and the 7500-kw.

on the Canadian side are ideal machines for 22,000 volts, by reason of their large capacities and the relations that exist between capacity and the number of poles.

In conclusion, after several years' experience in designing, I am confident that 22,000-volt generators properly selected in the matter of their ratings, offer less difficulties in design and construction than numerous 6,600-volt generators now in operation.

R. S. Kelsch (by letter): In June, 1905, the writer endeavored to purchase 25,000-volt, 3750-kw. generators for a hydroelectric development to consist of five 3750-kw. generators for an 18-mile transmission. Several large companies manufacturing this class of electrical apparatus were asked if they would construct such machines. One company replied that they did not think it feasible; the other companies thought it feasible but were not prepared to supply machines of this voltage at that time.

The plant referred to is now operating, using 3750-kw. generators, step-up transformers, etc. In preparing plans for this installation, and while considering 25,000-volt generators, the following points, for and against the use of such generators, received consideration:

Extra cost. Generators; potential transformers; current transformers, etc.

Saving. Saving of step-up transformers, building for transformers, generator cables, entire low-voltage bus-bar system, switches, etc., the water- and oil-pump system, insurance on transformers and building, interest, and depreciation.

Disadvantages. The 25,000-volt generators would be exposed to line strains, lightning, etc. In case of lightning entering the station, liability of greater damage and serious interruption to service, which might be overcome by extraordinary insulation on generators, and 25,000-volt bus-bar constructed to have had capacity to dissipate abnormal strains.

There is also the disadvantage that with such generators the multiplicity of voltages sometimes required for the high-tension systems could not be obtained as readily as with the step-up transformers.

Advantages. Advantages obtained by using the 25,000-volt generators are; better regulation, simplicity of station wiring, reduced fixed charges, reduced danger from fire due to the absence of oil-cooled transformers.

In Montreal there is one hydroelectric plant containing eight 750-kw., 4400–5000-volt generators, working direct on the transmission lines. In nine years' service there has not been one case of trouble on the high-tension windings of the generators, due to lightning or other abnormal strains. And this plant has yet to record the first injury to an employee or any other person from these 5,000-volt machines.

When this plant was installed, the specifications for these generators called for the insulation to be such as successfully to withstand a 25,000-volt alternating-current breakdown test.

The writer believes that a plant containing a large number of 25,000-volt generators can be successfully and safely operated.

L. Schüler (by letter): There is no doubt that alternators can be wound for pressures over 20,000 volts. As early as 1895 I assisted in the design of a 30-kw. 27,000-volt machine, which was built by the Allgemeine Elektricitats-Gesellschaft, Berlin. It worked satisfactorily. The coils were embedded in troughs of micanite, and the machine was made for the purpose of showing that the possibilities of this new (at that time) material.

Another question is, whether it is advantageous to use such machines in connection with long transmission lines; this I think is *not* the case. Mr. Behrend is quite right to advocate the carrying of spare coils, but it should be well understood that it takes at least a couple of hours to replace coils of an alternator, while practically no time is required to switch in a spare transformer. Even if no spare transformer is available, in case of a breakdown it will very often be possible to carry the load on the other transformers while the broken down one is being repaired. The overload capacity of alternators, and especially prime-movers, is usually not sufficient to do this.

As Mr. Behrend says himself, there would not be much saving in costs by the adoption of such extra high tension generators, I think it would be rather unwise for supply companies to use and for manufacturing companies to sell them.

Farley Osgood (by letter): Without question the operating dangers in a high-voltage machine are greater than in a machine of moderate voltage. The greatest objection the writer has to a machine wound for such a voltage is the uncertainty of protecting it from outside disturbances such as grounded or short-circuited lines, lightning discharges, etc. With step-up transformers, a defence-wall for the generating units is maintained, and the protection afforded is in my opinion worth the additional cost.

No doubt such a generator can be built and will run satisfactorily, but I think that the discussion would finally resolve itself more into one of practical operation rather than electrical or mechanical possibility. As an extreme case, Mr. Behrend cites as possible a 20,000-volt machine as small as 150 kw. capacity; such a machine would of course be built for experimental purposes only, as there is hardly any power problem which would require such an unusual piece of apparatus.

It seems to me that a machine wound for 20,000 volts to be used directly on the power system should receive consideration only where units of enormous capacity are required and where the transmission distance is very short.

H. F. Parshall (by letter): The practicability of winding generators for 22,000 volts would depend largely on the size of the machine. In the case of the proposed installation for the London County Council, where 12,000 to 15,000 kw. turbo-generating sets are in contemplation, the matter was the subject of most careful consideration, the result of which was that 15,000-volt generators were considered practicable and that they would be more satisfactory in practice than low-voltage generators with step-up transformers. Voltages higher than 15,000 were considered, both in the generating and transmission systems, the transmission system in this case being underground and thereby being subject to different considerations from an overground transmission system, and it was found that to transmit the same energy, having regard for all of the conditions, there would be no advantage in the transmission system is a voltage higher than 15,000; in fact, the maximum advantage occurred at that point.

I make particular mention of this in that the installation has been designed to distribute 250,000 kw. over perhaps the widest area that is likely to be encountered in municipal supply. This being, therefore, practically the limit of this class of installation, it would appear there is a natural division between voltages for generation in what may be termed a municipal system and in what may be termed a long-distance transmission system, the limiting commercial voltage for a municipal system placed underground being approximately 15,000 volts, whereas in the long-distance transmission, if overhead, three or four times this becomes commercial. At this higher voltage, direct generation is out of the question. It would appear, therefore, the particular answer would be that in practically every case generators of large size can be wound to meet the requirements of economical transmission in the largest type of municipal plant, but that in the case of long-distance transmission, step-up transformers in the generating station become a necessity.

A. Henry Pikler: The chief object in winding a generator for high voltages is to use it directly in connection with the transmission line and to do away with the step-up transformer, if this in combination with the generator is found more expensive than the high-voltage generator alone.

I assume that 22,000 volts was selected in connection with this paper, because it was thought that this is about the limit for which generators can be wound in the present state of the art. Since, however, there is a large range of transmission voltages still above 22,000—in such cases transformers must be used anyhow—I should more explicitly formulate the question like this: Is it practicable to operate transmission lines from 20,000 to 25,000 volts directly by generators wound for such voltages?

What is meant by practicable? By this term I understand collectively the following elements in question: 1. Whether or not the apparatus can be built at all for such a voltage. 2. Whether or not it is economical to the manufacturer to build it for such a voltage in preference to other solutions. 3. Whether or not such a generator is reliable in the service; that is, economical from the standpoint of the power-plant man.

The very fact that there is some discussion over the practicability of 22,000-volt generators, may readily convey the impression that winding generators, even large generators, for 22,000 volts, is a great feat. Generally speaking it is not. It is not the art of insulating that is at fault in this problem. It is not that materials cannot be found good enough or that we do not know how to do the insulating, in order to have the generators stand the voltage in service.

The author introducing this subject for discussion illustrates very well with his 150 kilovolt-ampere, 22,000-volt generator, operating for months night and day without a break, that this is not the case. Though it is true that the quality of insulating materials has undergone rapid progress during the last four or five years, yet I know of machines wound for 20,000 volts that were installed seven years ago. These machines are not very large. They are horizontal turbine-driven, 150-rev. per min., 15-cycle, 1000-kw. machines. They can operate at 30,000 volts for half an hour without injury and they are operating satisfactorily.

I know of another plant installed about a year ago with 4000-kilovolt-ampere turbine-driven generators wound for 40,000 volts, and they are working satisfactorily. To wind and insulate a generator for 20,000 volts is, then, not out of the question.

The most essential thing needed for winding a generator for high voltages is space, big slots where there is space for the slot insulation, for insulation between adjacent turns or layers, and space on the ends to prevent creeping or breakdown between the ends of coils.

Big slots, however, mean an uneven distribution of magnetic flux, strongly developed higher harmonics, an electromotive force wave-form deviating from the sine wave, a higher excitation. It would be very interesting to know the electromotive force wave-form of the 150 kilovolt-ampere 22,000-volt machine, of which other characteristic curves are shown to advantage in the paper.

This wave-form is a very important matter, the manufacturer should consider it just as much as he does the possibility of a satisfactory insulation or the cost of a machine. There is no doubt but that even a 2000 kilovolt-ampere 300-rev. per min., 20,000-volt machine can be produced at a lower cost than can a combination of a 2300-volt machine and three 700-kilovolt-ampere step-up transformers. Besides, it would greatly simplify the power plant and lessen the responsibilities of the station men. It is doubtful, however, whether such a generator would be as good in every other respect, especially in wave form, as the 2300-volt generator. Besides, selling a generator and transformer, too, means greater profit to the manufacturer.

As to the reliability. A generator if protected by lightning-arresters, choke-coils, or even static-interrupters against abnormal rises in voltage is, to my mind, a safer and simpler proposition than a combination of a generator and transformer;

on the other hand, if a breakdown occurs—in one case the transformer breaks and in the other the generator—there is no doubt but that it will take more time to repair the generator than to cut out the injured transformer and run the other two on open delta, or to repair the transformer, or to cut in a spare transformer.

Which solution is the most economical to the customer is almost solely dependent upon local conditions. For instance, in steel works or ore-smelting works where large blast-furnaces are electrically operated and where in case of a breakdown costly furnaces and valuable ore are affected, it will pay to carry in reserve even a complete generating outfit.

As the practicability in winding alternators for high voltages depends chiefly upon their geometrical dimensions, I cannot accept such a general conclusion as arrived at by the author of the paper. If he had in mind a steam turbine, he is about right, but I am of the opinion that lower generating capacities can be wound and used to advantage for 22,000 volts.

Bertrand P. Rowe: From the standpoint of the man who has to provide for the switching devices, the proposal to wind alternating-current generators for higher voltages than are commonly used at present seems to be a step in the right direction. As the size of unit increases, and the amount of energy to be interrupted becomes greater, it becomes more and more of a problem to build oil-switches that will open the circuits from the bus-bars, because the lower voltages now employed introduce currents of large capacity.

The problem of breaking circuits at high voltage has been successfully solved as far as pressure is concerned. It is a simple matter to open a circuit for any generator voltage that is likely to be determined upon. But if this circuit must carry a large ampere capacity, the problem becomes more difficult; and the higher the generating voltage becomes the simpler will be the problem.

Oil circuit-breakers have been built to open circuits carrying 2000 amperes normally at 13,000 volts pressure, and there have been cases where engineers have asked for circuit-breakers to open 3000-ampere circuits at 13,000 volts pressure. Here we are getting to the point in oil-switch design where it is doubtful engineering at best to build the switch and be ready to guarantee its successful operation.

If it were only the generator capacity that must be taken into consideration, it would be some time before arriving at a point where the switch must break any extraordinary current with present generator voltages. But the fact is that the use of low voltages on the bus-bars means heavy capacities in the junction and tie-in switches, and on circuits feeding large capacity transformer banks. The latter must often be automatic, and when opening on heavy overloads in a station with enormous capacities on the bus-bars, the result may be imagined. As the entire operation of a plant may depend on the success or failure of such switches, connected as they are to the bus-bars, the importance of this phase of the situation is obvious.

The problems involved on account of higher generating voltages in the other switchboard apparatus and the wiring of the station are not worth mentioning. The only appreciable difference will be that the higher potential will have to be provided for in the cables between the machines and switchboards. It is really a installation problem that has already been solved.

Comparing the cost of switchboard apparatus and conductors, everything is in favor of the higher voltage. It may cost a little more for insulated cables, but the oil circuit-breakers, bus-bars, series transformers, and other accessories will be smaller in capacity and much cheaper. It often happens that switchboard apparatus for a 13,000-volt plant with a given ampere capacity can be used without change for a plant of the same capacity at 22,000 volts, for the reason that the manufacturers have one class of apparatus for both purposes.

Summing up the whole situation, the use of higher generator voltages will simplify the problem in the switchboard equipment, and undoubtedly reduce the cost, besides involving nothing that has not been well developed and in successful operation.

A. B. Reynders (by letter): High voltages are independent of the prime mover; that is, the insulation on a 22,000-volt generator would be practically the same whether driven by hydraulic turbine, gas engine, reciprocating steam engine, or steam turbine.

As stated by the author, increase of voltage means increase of conductors. Increase of conductors means increase of insulation; hence, the higher the voltage the greater percentage of slot space occupied by the insulation. This, from a mechanical point of view, is inefficient. In the case of the 11,000-volt generator, cited by the author, it is probable that 50% of the space in the slot was taken up by the insulation, the remaining 50% being copper. Increasing this voltage to 22,000 volts and the capacity to 15,000 kw. will cause the insulation to be doubled; or, in other words, the space occupied by the insulation will be 70% of the total slot space.

When it comes to the insulation on the ends, the distance which the bare parts of the coils will have to project will be about double that required for 11,000 volts. This means that the coils will be extremely weak mechanically, owing to their length. This assumption is based on the fact that peripheral speeds cannot be increased much over the present uses; hence the increased induction must be obtained by lengthening the iron.

The increase in insulation has another very bad feature besides occupying valuable space; namely, it is a non-conductor of heat. All heat generated in the copper must be transmitted to the surrounding cooling medium through the insulation. Under the action of heat all insulation of a fibrous nature tends to deteriorate. Mica and asbestos are exceptions, but these are grave objections to their use unless combined with some fibrous material, such as tape. This deterioration of insulation is reduced by decreasing the heat generated, to accomplish which necessitates an increase in the size of copper. This again tends to decrease the efficiency per pound of gross weight.

As admitted by the author, a 22,000-volt generator is less reliable than one of 11,000 volts. That this is a grave weakness is endorsed by his statements regarding spare parts. He recommends practically an extra machine to provide against breakdowns. The only advantage which can be claimed is in simplicity of the power station by avoiding use of transformers.

Guido Semenza (by letter): Mr. Behrend rightly points out that the reason for using high-tension generators is to limit their current capacity, as the distribution and conduction of large currents from the generators to the switchboards is cumbersome and expensive. I would add, that up to a certain point switching with high pressure is preferable to switching with very heavy current.

In his comparison the author refers very likely to central stations having such a switchboard scheme that the low-tension generator currents are collected on a set of bus-bars to which the low-tension circuits of the transformers are connected, and, as far as such scheme is considered, I quite agree with him in his conculsions. But there is an intermediate solution between this and the use of high-tension generators which is employed in some European plants. Low-tension generators are used, and each generator is connected to a set of transformers, with circuit-breakers; there are no switches, no fuses, nor instruments being used in this low-tension connection.

The generator and its transformers are considered as a high-tension generating unit, and all the switchboard is on the high-tension side of the transformers. Such a solution permits of all the advantages of low-tension generators, confines the high-tension in an apparatus much more fit to withstand it, and at the same time reduces the current capacity in the switchboards.

It has only one apparent drawback; that is, that a fault in a transformer will also put a generator out of service; but if the use of low-tension will have the effect of reducing the number of accidents in the generator, then there will still be an advantage, as the repairing of generator coils requires much more time than the time required to replace a faulty transformer with a spare one.

Philip Torchio (by letter): Referring to Mr. Behrend's question as to what part the ohmic resistance plays in the parallel operation of synchronous apparatus on long transmission lines, I wish to call the attention of the parties interested in this subject to a paper contributed by Mr. G. Semenza to the Milan section of the Associazione Elettrotecnica Italiana, at their meeting of December 4, 1903.

The paper describes two series of tests: one upon two direct-current synchronous motor-generator sets, operated inverted from a large storage-battery and with the alternating-current machines connected through an adjustable resistance. The other series of tests was made on a synchronous motor fed from the main bus-bars of a large generating station through an adjustable rheostat. In both cases the load and power-factor and reactance and ohmic resistance of circuits were adjusted for different values so as to obtain curves showing the behavior of these machines. Pumping phenomena would appear in all instances under certain conditions of load, power-factor, and ohmic resistance of the circuit. The pumping had a frequency of from eighty to one hundred and twenty vibrations per minute, and beyond certain values the amplitude of the oscillation was so large that the machines were thrown out of step.

Mr. Semenza's analysis of the results gives lucid portrayals of the function of resistance and reactance in a circuit upon the parallel operation of synchronous motors, and possibly might be abstracted for the minutes of the Institute, or at least attention called to this contribution to the subject for the information of those who may care to look up the subject.

John Pearson (by letter): I agree that there are advantages in winding large alternators for 22,000 volts, especially when this is the potential required for distribution. As Mr. Behrend says, steam turbines will probably soon be built for 10,000 to 25,000 kilowatts. These large steam units will naturally be used in large cities where the distance of transmission is relatively short. Hydraulic turbines in the near future will possibly range in capacity, as at present, from 1,000 to 3,500 kilowatts. These turbines will, on the average, be used at a distance from the market or center of distribution, where the distance of transmission will be relatively long.

I believe it practicable to wind 22,000-volt alternators for use with large steam turbines where the distance of transmission is short. In this case, power stations using 22,000-volt alternators will need no step-up transformers, resulting, of course, in higher efficiency. The danger of generator coils being punctured directly by lightning will be small, as the average turbo-generator will be transmitting its power through underground cables.

The transmitting voltage of the future water-power station is likely to be from 60,000 to 100,000 volts, and one would not favor using, a 20,000-volt alternator where the transmitting potential was 60,000 or 100,000 volts, as transformers for raising the potential would also have to be used. Where step-up transformers have to be used, I believe it practicable to use generators wound for 2,200 volts, as there is very little danger of the generator coils giving way at this voltage.

A generator wound for 22,000 volts can, as far as insulation is concerned, be compared to an air-blast transformer. I know by experience that the oil-insulated transformer will stand more severe static strains than the air-blast transformer. Consequently, a 20,000-volt generator cannot be expected to stand up under severe static strains any better than can the air-blast transformer, on account of not having the benefit of oil for insulation. Oil simply for insulation is not all, as the oil fills all intermediate space between and around the coils and thereby keeps the dirt away from the coils, which is one good point.

Mr. Behrend states that the insulation of coils against ground is easier to obtain than against one another, and that the question of insulating the coils from one another is particularly difficult in turbo-generators on account of the crammed conditions of the winding space. From the above it is seen that no more insulation can be used than what is absolutely necessary; but it is comparatively easy to bring out leads and use cylinders and air-gaps, as shown in TRANSACTIONS A. I. E. E., 1904, Vol. 23, p. 570. Also TRANSACTIONS A. I. E. E., 1905, Vol. 24, pages 960-962-978.

I know by experience that when using spark-gaps across each coil, less insulation can be used, as abnormal strains are equalized over the whole winding. I do not consider it hard to insulate a generator for 22,000 volts under normal conditions, but such generators must stand up under abnormal static conditions as well.

It seems wise, therefore, to use spark-gaps across coils, the winding connected in star and the star and core grounded. By this arrangement the generator becomes to a certain extent a condenser, having capacity between coils; between coils and the frame, between coils and the ground, this capacity becomes more noticeable when any static strain can reach all parts of the winding at once, than if it only piled up on the first coil nearest the transmission line.

A paper presented at a meeting of the Chicago Branch of the American Institute of Electrical Engineers, Chicago, Ill., March 26, 1907.

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HIGH-VOLTAGE DIRECT-CURRENT AND ALTERNATING-CURRENT SYSTEMS FOR INTERURBAN RAILWAYS.

BY W. J. DAVIS, JR.

The magnitude and direction of engineering development in apparatus for the electrical equipment of high-speed interurban railways is well illustrated by a study of the systems adopted by some of the more important lines recently built or now under construction. These systems may be divided into three classes, namely:

1. 600-volt, direct-current using either overhead trolley or third-rail.
2. 1200-volt, direct-current overhead trolley.
3. Single-phase, alternating current, 3300- or 6600-volt overhead trolley.

As apparatus for the operation of the 1200-volt, direct-current system is being manufactured in this country only by one company, the list of roads given below comprises only those using equipments manufactured by this company, and is limited to sales to new roads made during the last year.

The largest installation undertaken during the last year was that of the West Jersey & Seashore Railroad, comprising equipment for 145 miles of single track and 35600 h.p. in railway motors. On account of the limited time required for the completion of this installation (six months from date of selecting power-house site) it was impossible to furnish apparatus of special type, making the selection of the 600-volt, direct-current system obligatory. For this reason the equipment of this road is not included in the following statistics.

	Length of track	No. of Cars	Size Motors	Total motor h.p.
600 *volts, direct current*...........................				
Texas Traction Co..........................	63 miles	15	4 75 h.p.	4,500
Elmira, Corning & Waverly..................	15 "	7	4 60 "	1,680
Buffalo, Lockport & Rochester...............	70 "	19	4 75 "	5,700
Oregon Railway............................	40 "	8	4 75 "	2,400
	188 "	49		14,280
1200 *volts, direct current*........................				
Central California Trac. Co.................	16 miles	6	4 75 h.p.	1,800
Pittsburg, Harmony, New Castle & Butler.....	63 "	12	4 75 "	3,600
Indianapolis & Louisville....................	41 "	10	4 75 "	3,000
Indianapolis, Columbus & Southern...........		3	4 75 "	900
San Jose & Santa Clara......................	9 "	8	4 75 "	2,400
	129	39		11,700
Single-phase, 3300 *or* 6600 *volts*..................			4 125	
Washington, Baltimore & Annapolis..........	52 miles	25	2 125	11,500
Central Illinois Constr. Co....................	40 "	10	4 75	3,000
Anderson (S .C.) Railway....................	35 "	3	4 75	900
Richmond & Chesapeake Bay................	15 "	4	4 125	2,000
	142	42		17,400

Total horse power in motors sold, 43,380 of which
600 volt, direct current has 33 per cent.
1200 " " " " 27 " "
Single phase alternating current has 40 per cent.

It is most interesting to note that two-thirds of the total motor capacity sold consists of 1200-volt, direct-current and single-phase alternating-current motors, indicating the eagerness of electric railway builders to take advantage of the reduced cost of construction and equipment, and economies in operation, resulting from the use of higher secondary distributing voltages. The magnitude of the possible savings will depend upon the local and service conditions and will vary over a wide range.

Generally speaking, increased voltage at the trolley will be attended with reduction in cost of copper and sub-station apparatus, and by increased cost of car equipments due to the inherently heavier and more expensive character of the motors and control systems. Where the car movement is especially frequent, as in case of rapid-transit suburban service in the vicinity of the larger cities, requiring from two to four tracks, the 600-volt, direct-current systems will generally prove the cheaper, a result largely due to the lower cost of the motors.

On account of the variable character of the conditions encountered, each problem requires a special investigation before the relative merits of the three systems can be reliably determined, but the following general limitations will be found to hold true.

1. Street railways and elevated roads in cities should unquestionably be equipped with standard 600-volt, direct-current apparatus.

2. Suburban lines 10 to 15 miles in length operating cars on frequent headway should be equipped with 600-volt, direct-current system.

3. For high-speed interurban railways operating cars 50 ft. or more over all at speeds of 40 miles per hour or more:

a. The 600-volt, direct-current system is the most reliable on account of being most fully developed.

b. The 1200-volt, direct-current system is somewhat cheaper in cost than the 600-volt system, but is as yet an untried system.

c. The single-phase, alternating-current system will in most cases show material saving in cost over the direct-current systems, and has been developed to a point where it may be considered commercially successful and capable of giving satisfaction in operation, if properly proportioned for the service to be performed.

There are certain conditions which render the alternating-current motor system unduly expensive or impracticable; namely, the enforced use of a frequency greater than 30 cycles, the presence of grades greater than 8 per cent., or the necessity of obtaining perfectly balanced three-phase load under all conditions. In such cases, the 1200-volt or the 600-volt direct-current system will prove the most economical, preference being given to the latter although the cost of installation will be greater.

The single-phase, alternating-current and 1200-volt, direct-current equipments may both be made to operate satisfactorily on standard 600-volt, direct-current systems, and assuming equal reliability, the question becomes one of first cost and economy in operation. The following table will show approximately the relative cost of a typical suburban road with the several systems.

It is of interest to compare the operating economy of the three systems, eliminating those items which are of equal value in each. The comparison given below is based on coal at $3.00 per ton; coal consumption 3.5 lb. per kilowatt-hour; sub-station attendance $1750 per annum; maintenance of car equipments, 0.4c. per car-mile for 600-volt direct current, 0.5c. for 1200-

volt direct current, and 0.6c. for alternating current, and fixed charges at 10.5%.

COMPARATIVE COST PER MILE, SINGLE TRACK.

	Direct current 600 volts	Direct current 1200 volts	Alternating current 6600 volts
Roadbed complete including grading, ballasting, etc.	$15,000	$15,000	$15,000
Trolley and feeder installed	3,800	3,000	2,100
Track bonding	600	530	480
Transmission line, installed	1,500	1,500	1,300
Sub-stations, installed	2,200	1,600	600
Power station, installed	2,450	2,450	2,570
Cars and equipment	1,800	1,970	2,300
Telephone	120	120	120
Total	$27,470	$26,170	$24,470
Saving over 600 volts, direct current		1,300	3,000

RELATIVE OPERATING COST PER MILE SINGLE TRACK PER ANNUM.

Per mile of track, one-hour headway	Direct current 600 volts	Direct current 1200 volts	Alternating current 6600 volts
Car-miles per day	64	64	64
Kilowatt-hours per day at power house	275	275	245
Cost of coal per annum	470	470	419
Cost of sub-station attendance	175	79	46
Maintenance of motors and control	94	117	140
Total	$739	$366	$605
Saving over 600-volt direct current exclusive of fixed charges		73	134
Saving in fixed charges		137	315
Total annual saving		$210	$449

Another method of comparison is to capitalize the annual saving exclusive of fixed charges. Assuming fifteen years as the average life of equipment and construction work, the present value of the annual saving in operating expenses per mile of track at 5% interest will be:

For the 1200-volt, direct-current system	$ 756
To which add saving in first cost	1300
Making the total capital value of	$2056 = 7.5%
And for the 6600-volt, single-phase system	1390
To which add saving in first cost	3000
Making total capital value of	$4390 = 16%

The above comparison is based on service and construction conditions applying to the typical high-speed interurban electric railway, the fundamental assumptions and principal data being as follows;

Length of road, 50 miles or more.

Cars 52 ft. over all, weighing 21 tons without equipment or load and seating 56 passengers.

Car equipment, four 75-h.p. motors.

Maximum speed on tangent level track, 45 miles per hr.

Schedule speed 24 miles per hr. including stops and slow running through towns.

Headway, maximum service, 0.5 hour.

Frequency of stops, one in two miles, interurban.

Average car energy, 85 watt-hours per ton-mile at car.

	Direct current 600 volts	Direct current 1200 volts	Alternating current 6600 volts
Cost of cars equipped	$10,800	$11,800	$13,800
Spacing of sub-stations	10 miles	22 miles	32 miles
Maximum voltage drop, trolley line	25%	25%	10%
Efficiency of system, generator bus-bars to cars	71%	71%	84%
Average efficiency car equipment	75%	75%	73%
Average power-factor of system	96%	96%	85%

As the 1200-volt, direct-current system is still in process of development, a brief description may prove of interest.

The roads which are now being equipped may be divided into three classes: 1. Those which are required to operate on 600-volt direct current at full maximum speed as on the 1200-volt sections; 2. Those which are required to operate on 600-volt direct current but at approximately half maximum speed; and 3, those which operate only on 1200-volt trolley.

The first class requires motors wound for 600-volts but designed to stand 1200 volts without danger of flashing or injury to the insulation. The motors are connected four in multiple when run on 600 volts and in two parallel groups of two motors in series when run on the 1200-volt sections.

In the second and third classes the motors may be wound for either 600 or 1200 volts, preference being given to the latter on account of improvement in tractive power at the slipping point of the wheels. In order to obtain satisfactory commutation qualities and to control the tendency to flash at the commutator at the high voltages encountered, all motors for the 1200-volt system are provided with a compensating winding in the shape of series wound auxiliary poles located midway between the magnetizing poles and so proportioned as to neutralize the armature reaction under all loads. The additional insulation required causes the motors to weigh 15% to 20% more for a given output than 600-volt motors. This additional weight is not due to the inter-pole construction, as on the basis of equal voltages the inter-pole motor will weigh about the same or a little less than the standard railway motor.

The control system is substantially the same as that used on the 600-volt system, with the exception of some slight changes in the insulation of the primary circuits. The secondary circuits are all energized at 600 volts, as are also the car heaters and lights, and for this purpose a small dynamotor is furnished for use when run on 1200 volts, the function being to change the voltage to 600. The capacity of this dynamotor as furnished with quadruple 75-h.p. equipment is 38 amperes, which provides for the lighting, heating, and air-pump circuits for one car, and secondary control circuit for a train of six cars.

DISCUSSION ON "HIGH-VOLTAGE DIRECT-CURRENT AND ALTERNATING-CURRENT SYSTEMS FOR INTERURBAN RAILWAYS," AT THE CHICAGO BRANCH, MARCH 26, 1907.

James Lyman: No branch of engineering is more active than that engaged in the electrification of transportation systems, so Mr. Davis' paper is as timely as it is interesting and instructive. The network of interurban railways in the middle West is one result of this activity. There is one system of electric railways centering in Indianapolis having 400 or 500 miles of road, and another in the central part of Illinois having about 300 miles of road, with 150 miles more now under construction.

Mr. Hesing: It has been pretty well demonstrated what the 600-volt, direct-current motor will do, but possibly it is not quite so well understood what the alternating-current motor will do. Just at present I have charge of a little alternating-current line, and maybe a short description of what we do will be of some interest. We operate at 3300 volts. The line is about 22 miles long, with no sub-stations whatever. We have a 00 trolley wire. In fact, we started out with two 00 trolley wires, and one was moved over to the pole and now acts as a feeder. The cars are not very large, about 35 tons, requiring 75-h.p. motors. To my mind, the operation has been very satisfactory. Our records show that the cars have run from 75,000 to 85,000 miles with only one furbishing of the commutators, and they run from 5,000 to 6,000 miles with one set of carbon brushes. We subject our cars to pretty severe treatment. They are geared for 42 miles an hour, and as the road is quite small and sometimes pushed beyond its capacity, a couple of ordinary flat cars are used for trailers, side boards are put around them and folding-chairs are provided. These are called "chair cars", and probably 600 or 800 people are hauled at a load. It doesn't look very nice, but it pays.

I am glad that the speaker says the alternating-current system is of so much value. I can hardly see how it can be improved upon, except in one particular—the acceleration of the motors is slow. Our stops are not frequent, but where, as in the city practice, stops are very frequent, I think the service would be a little bit slow. Paralleling the Alton, when we made a run for that, we had no trouble whatever to give the same service as the expensive red train. So I think that for a little road—really an experimental road—the alternating-current system is the thing to use.

Mr. Gould: Having had experience only with the standard 600-volt, direct-current system, I am more in the nature of a questioner. I would like to ask Mr. Davis as to the relative costs of maintenance of the line and trolley system of the two; that is, how much does the line maintenance of the alternating-current system exceed that of the 600-volt, direct current-system?

W. J. Davis, Jr.: The single-phase system has not been in operation sufficiently long to permit complete standardization of the line material. Such experience as we have had, however, indicates that a 6600-volt overhead trolley system using catenary construction may be made very reliable and durable, and should give a maintenance cost at least equal to the best 600-volt, direct-current construction.

Peter Junkersfeld: In making comparisons on the cost, I notice that Mr. Davis has used a figure of 10.5% fixed charges and he has applied that to all three systems. It seems to me from what I have heard and from what Mr. Davis has told us, that if 10.5% is fair for the 600-volt system it is liable to be somewhat low for the other two systems, for the reason that they are somewhat new and untried. It seems quite low to me even for the 600-volt system.

W. J. Davis, Jr.: That 10.5% does not represent maintenance. It simply represents interest, taxes, insurance, depreciation, and charges of that nature, with interest at 5%. These are independent of the kind of system used. The depreciation has been taken the same for each system; that is, life of buildings 40 years, copper and line equipment 20 years, rolling stock 15 years. These values are rather low than otherwise for a good system. It is possible to get more than 15 years out of modern car equipments, if well maintained.

Peter Junkersfeld: What I have in mind is, on the new and untried systems there would be quite a considerable "antiquation charge"; that is, the system will probably be perfected a great deal more in the next five or ten years, and part of the equipment will probably then be obsolete.

W. J. Davis, Jr.: That is true. Taking that into consideration the fixed charges should be somewhat higher.

Peter Junkersfeld: And that in time would make it a little more favorable to the 600-volt system. Another question: how does the maximum allowable drop compare in the two systems?

W. J. Davis, Jr.: The maximum momentary drop permissible in the 600-volt system should not, as a rule, exceed 50%; most systems are usually calculated for about 25%. The latter condition will give about 5% average energy drop, depending upon the frequency of the service, grades, and other conditions. In the 6600-volt, single-phase system the average allowable drop in the secondary distributing system is usually fixed at 5%, including that in the rail return, with swings approaching 10%. It must be remembered that in the alternating-current system the drop in the various sections between the car and the power station bus-bars is cumulative. In addition to the drop in the trolley line and track, there is an energy drop and reactive drop in the step-down transformers, transmission line, and step-up transformers. Finally, there is the regulation of the generators and the drop in speed of the engines when the car starts. These are all cumulative in their effect. In a direct-current system, on the other hand, we have only to consider the drop from the sub-station bus-bars to the car. For the above reasons it is necessary and desirable to allow a much smaller maximum drop in an alternating-current system than in a direct-current trolley system. A maximum voltage drop of 10% in trolley and track of a single-phase system will often correspond to 25 or 30% drop in the whole system.

W. A. Blanck: Mr. Davis makes a statement about 40% of these roads being single-phase roads. I must say I have enjoyed the statement very much, because we have tried in the middle West to find railways on which we could use the single-phase system. Most of those we have investigated found it almost prohibitive to use the single-phase system, because of exchanging rolling stock with other roads and running into the cities where direct current is used. Furthermore, we find it very difficult always to use high potential in the cities themselves. Is it possible to overcome these difficulties? Most of our systems run into cities where we can not use the alternating-current system to-day.

Mr. Davis proposes to put the sub-stations about 32 miles apart, which would give 16 miles on each side for one section. That is rather long and it makes the section dependent on any kind of breakdown in that long section, so that more subdivisions with feeders or more frequent sub-stations will be required. Have these questions been investigated, and has any difficulty been found in placing the sub-stations so far apart?

W. J. Davis, Jr.: I do not think it necessary to place sub-stations closer together, because of possible unreliability in the secondary distributing system. It might be well to have a switch on a pole suitably located so that a part of the line may be cut out for repairs. If the line is properly erected, a 30-mile section, where cars are operating normally on one-hour headway with a maximum of one half-hour headway, ought not to be considered excessive in the light of past experience. The time may come in the development of the alternating-current system when sub-stations will be omitted entirely and 11,000 volts will be fed direct into the trolley with power stations located 30 to 50 miles apart. If the load-factor is sufficiently good to warrant the use of this arrangement, the system is reduced to the basis of the ordinary city railway system so far as simplicity and reliability are concerned. Some of the 6600-volt, single-phase roads now being installed will feed out 15 or 16 miles from one sub-station.

W. A. Blanck: It is necessary to enter cities with interurban roads. If steam-road conditions prevailed, if there were isolated terminals, an alternating-current system would be practicable, but interurban roads generally terminate in a city, and must operate therein by the direct-current system. We are all convinced that the alternating-current system is a coming system—much less investment for same amount of traffic done—but present operating conditions almost make it prohibitive to put it in.

W. J. Davis, Jr.: So far as the motor is concerned, the alternating-current motor can be built to operate as well on direct current as the ordinary direct currrent motor. Several instances have come under my observation where a combination of the 600-volt, direct-current and 6,600-volt single-phase sytems has made it possible to secure an increased economy in operation and also a considerable saving in cost.

I have in mind the case of a road 65 to 70 miles long. On the first 15 miles the service will be extremely heavy, requiring the operation of two- or three-car trains on 15-minute headway with frequent stops. The rest of the road will require the service of single cars every hour. There will be required a rolling stock equipment of about 30 cars, of which 25 will operate on the 15-mile suburban section and the remaining five on the longer interurban section. A straight single-phase system will prove objectionable on account of the intrinsically higher cost of the car equipments, due to the frequent service. on the other hand, the straight direct-current system will prove expensive on account of the larger number of synchronous converter sub-stations required on the 40-mile interurban section. A combination of these two systems, the 15-mile suburban system being equipped for direct current and the 40 miles interurban section for alternating current, will prove cheaper in first cost and more economical to operate than either system considered separately. This combined system will require two alternating-current sub-stations on the 40-mile interurban section, two direct-current sub-stations on the 15-mile suburban section, twenty-five direct-current equipments, and five single-phase equipments. The objection from an operating standpoint of having two types of motors is more than counterbalanced by the possibility of securing the most desirable operating features of both systems with the objectionable features of each reduced to a minimum.

T. F. Clohesey: What is the relative efficiency of these motors while running? For instance, a 300-h.p. car at full load alternating current and then when it enters a city and has to operate on direct current? What is the efficiency of the same car provided there are no stops?

W. J. Davis, Jr.: It will be about 2% better on direct current than on alternating current.

W. A. Blanck: Have you overcome all the difficulties now in regard to interference with telephone lines? I have heard that in the East especially there are frequent complaints from telephone subscribers in the interurban districts—they have complained of interference with the service.

W. J. Davis, Jr.: There were complaints in the early days, because we had no operating experience with the actual conditions existing between the telephone lines and the single-phase lines, but within the last year we have found out how to cure all of the troubles. I do not know of a single case where, if proper consideration is given to the system when it is first put in, there should be any trouble with the telephones.

W. A. Blanck: There is another very interesting question to be settled—the bow versus the trolley. In the different tests mentioned, which arrangement has been used for collecting the current from the conductor?

W. J. Davis, Jr.: That question is probably the most vital of the whole alternating-current system. No overhead collecting device has yet been devised which experience has shown to be safe and reliable and to have a low maintenance at a speed exceeding 60 miles an hour. The third-rail is the only system which has been proved to be absolutely satisfactory. There have been several bow collectors designed, but none of these has been operated long enough to show exactly what maintenance could be expected from it. After a little more experience we may probably produce some form of collector which will have a longer life than the present form.

W. A. Blanck: What difficulty have you experienced in regard to the suspension of the trolley wire in the catenary form. Where the suspension points are less than three feet apart, do you find in running 60 miles an hour that each point gives a particular shock or kick to the bow, or do you overcome these difficulties? Have you been able so far to see what it will take to keep up the catenary construction work? Have you any data on these matters?

W. J. Davis, Jr.: No; we haven't any data to cover any period of time of sufficient length to be reliable. The suspension points in my opinion ought to be 15 to 18 ft. apart; this spacing giving the best results at high speeds where bow collectors are used. Where a wheel collector is used, the spacing between suspensions may be made 50 ft, or about three to the interval between poles.

W. A. Blanck: Have you found it necessary in your exerience to bond both tracks for single-phase service? or do you think it is sufficient to have only one track rail bonded, and in case of double track to have one cross-bond every half mile or so, or do you find it necessary to put a bond on each track?

W. J. Davis, Jr.: It 's usual to bond both tracks, because of greater safety, but I do not think there would be any great danger if only one track were bonded. In many high-tension systems a ground wire is carried on the poles as a lightning protection. If that ground wire were connected to the rail at suitable intervals trouble would be prevented.

W. A. Blanck: My special question with reference to that is whether one of the rails can not be used for signal service, and if it is what interference is there from having only one rail bonded and alternating current in one rail, while perhaps there is another frequency for single phase in the second rail, which I understand to a certain degree is used in the New York Central.

W. J. Davis, Jr.: I do not know of any case where that arrangement is used, but I can think of no objections to it. It would appear to be perfectly safe if a ground wire is run in connection with the track return.

L. M. Zapp: Mr. Davis, in his statement as to direct-current efficiency, said I think 71 per cent. from power station to the car on 600 volts. Is not that rather high?

W J. Davis, Jr.: The value given is based on 90% efficiency for the trolley system, 83% for sub-stations, including transformers and synchronous converters, and 95% for the transmission line.

L. M. Zapp: Of course that would depend on the load-factor and also on the magnitude of the system, whether it is only a 50-mile system operating from one power station, or a 300-mile system. The load-factor on an interurban line operating half-hour or even hour schedules will very seldom be greater than 35%, if storage-batteries are not used. May I ask Mr. Gould if he remembers just what his figures are?

Mr. Gould: They will not average 35%.

W. J. Davis, Jr.: Do you remember what your efficiency is?

Mr. Gould: About 75% from the sub-stations bus-bar.

L. M. Zapp: In a paper written by Mr. A. S. Richey, electrical engineer of the Indiana Union Traction Company, he said that the average efficiency of transmission from power station to the car motors on that system was a little better than 56%. That was on about a 300-mile, single-track system. I was connected with that road, and I remember that with 13 sub-stations we got an average efficiency from power station bus-bars to substation bus-bars of about 70%. The sub-stations would average about 15 miles apart. The feeder was nearly all 500,000 circular mils. Mr. Richey's later tests showed that the average efficiency to the car motor was only about 55 or 56%. That being the case, it would make the figures still more favorable to the alternating-current railway.

I. E. Brooke: In the alternating-current system with substations 32 miles apart, what system of lightning protection is used for the catenary? Is there any other protection than that at the sub-stations themselves?

W. J. Davis, Jr: I think it would be well to have lightning-arresters more frequently than at the sub-stations. It is usual to place pole arresters about one mile apart.

I. E. Brook: It is a simple matter in a direct-current system to put up a lightning-arrester on a pole every 1000 ft. or so. ith 6000 volts it is a different proposition.

W. J. Davis, Jr.: Yes; they should be boxed in.

I. E. Brook: What are railway engineers doing at present with three-phase motors for heavy power work? Has that proposition been dropped or are they still considering it?

W. J. Davis, Jr.: There is quite a well defined field for the three-phase motor. That field, however, apparently does not exist in interurban railway work, but it has been found to be especially applicable to hauling trains on heavy mountain grades reaching 2% and 2.5% and covering sections of 10 to 30 miles. By the use of the three-phase motor, it is possible without material complication in the control system to return power to the line on descending grades. Power saved by such regeneration is of secondary importance, however, as the greatest gain is made by the saving in wear on wheels and brake-shoes.

The company with which I am connected has not yet built a locomotive of this type, but a large number of designs have been investigated, and there are no physical reasons why such locomotives cannot be built as powerful and as reliable as direct-current or single-phase locomotives.

H. R. King: What is the character of the station in a 1200-volt-direct-current equipment; that is, the character of the generator equipment?

W. J. Davis, Jr.: With one exception the roads now being built will use two synchronous converters connected in series. It is perfectly feasible to build reliable 1200-volt, direct-current generators or synchronous converters.

Mr. Hatch: In regard to the 1200-volt line now building from Seymour to Sellersburg. If I remember aright the current out of Indianapolis is 550 volts; then there is a stretch using 1200 volts, and on the other end of the line I believe it is 650 volts. Will they be able to run any car clear through on that line?

W. J. Davis, Jr.: Yes; the motors will be wound for 600 volts, and on the 550- and 650-volt sections they will run at full maximum speed with motors in multiple. For 1200 volts, the motors will be connected in groups, two series, two multiple.

Mr. Hatch: Would there have to be very much change in an ordinary direct-current car to do that?

W. J. Davis, Jr.: No; simply having a commutating switch which will change the grouping of the motors as the car passes from one section to the other.

Mr. Hatch: Practically the same speed?

W. J. Davis, Jr.: Yes. The volts per motor will be the same for 1200- as for 600-volt operation. There may be cases where it is desirable to run at half speed on the 600-volt section; namely, within city limits. Here it might be well to use a 1200-volt motor, although the same result can be obtained by connecting in series-multiple groups, using 600-volt motors.

E. N. Lake: What rate of acceleration have they been able to attain with the later single-phase equipments?

W. J. Davis, Jr.: That depends on the size of the motor and gear-reduction. Most interurban single-phase cars, geared for 40 to 45 miles an hour with four 75-h.p. motors, 42-ton car, will give about one mile per hour per second rate of acceleration. As a matter of fact, it is not essential to have a very high rate of acceleration for interurban work, because the stops are infrequent (averaging about one in two miles) and the difference between one mile per hour per second and a mile and a quarter per hour per second, would not materially affect the running time.

James Lyman: Mr. Junkersfeld has referred to the depreciation percentage. Mr. Davis' figures are, I think conservative. In the development of a new line of apparatus, like this alternating-current–direct-current car equipment, it is understood that there are some features that undoubtedly will become obsolete after a time and will have to be replaced. There is also a good deal of apparatus that can be depended upon as reliable and as slow in depreciation and good for many years. The question that confronts the railroad engineer is whether it is not better on new work where the conditions are favorable to get in line at the start for the alternating-current type of apparatus that will soon become standard practice and which will eventually, if not at once, show marked economy over the standard 600-volt, direct-current system.

A paper presented at the 217th meeting of the
American Institute of Electrical Engineers,
New York, March 29, 1907.

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LIGHTNING PHENOMENA IN ELECTRIC CIRCUITS.

BY CHARLES P. STEINMETZ.

1. Originally lightning denoted electric discharges between clouds or between cloud and ground, and, when applied to an electric circuit, the results of such a discharge striking the line. Later it was found that during atmospheric disturbances, such as passing thunder storms, disturbances occurred in electric circuits even without the discharges striking the line. These disturbances, caused by induction, were also classed as "lightning," and applied to electric circuits, lightning then came to mean all the effects of atmospheric electricity.

With the introduction of electric circuits of higher voltage and larger electrostatic capacity, phenomena were observed in such circuits of the same character and effect, and requiring the same protective devices, as the disturbances caused by atmospheric electricity, even in cases where atmospheric effects were excluded, as in underground cable systems. The term lightning when applied to electric circuits, therefore, was extended to cover also these effects, which are due to internal circuit changes, as changes of load, discharges through weak places of the insulation, etc.

The damage done by lightning to telegraph and telephone circuits being relatively small compared with the disastrous effects occasionally occurring in high-potential systems of large power, it was acknowledged that frequently most of the damage is done by the power generated in the system; the atmospheric or other disturbance merely started the phenomenon. The term lightning was thus once more extended to include all the abnormal phenomena of the flow of generated power of the system which result from an atmospheric or other disturbance.

In its most general meaning, as understood now when dealing with electric circuits and their protection, *lightning denotes all phenomena of abnormal voltage and abnormal frequency.*

The lightning phenomena in electric circuits then comprise:

External lightning, the disturbances due to atmospheric electricity.

Internal lightning, the disturbances due to defects of the circuit or its operation, etc., and

Surges, that is, disturbances in the flow of generated power, brought about by the external or internal lightning and depending for their energy on the power of the generator system, hence frequently destructive.

2. The phenomena of abnormal voltage and frequency in electric circuits are the same three classes of phenomena met with in the disturbances in any medium which is the seat of energy:

1. Steady stress or gradual electric charge.
2. Impulse or traveling wave.
3. Standing wave or oscillation and surge.

1. *Electric Charge.* The potential difference against ground, or pressure of the total electric circuit, may gradually rise by an electric charge accumulating in the circuit—just as in a body of water, a river, the height may gradually rise until the water breaks through the embankment—the electric charge discharges across the lightning-arresters, or punctures the insulation, whichever is the point of least resistance.

Some causes of such steady and gradual accumulation of electric charge, and of potential difference against ground, of an electric circuit, are:

a. Collection of static charge from rain, or snow-drift, or from fog, carried by the wind across the line. Illustrating this on a three-phase system with insulated neutral, it will be seen that the potential difference against ground, which normally is symmetrical, Fig. 1, Curve I, gradually, by the simultaneous static charge of all three lines, changes to Curves II, III and IV, until the maximum potential difference against ground is sufficient to discharge to ground. The system then returns to the condition Curve I, and then traverses the same cycle again. This electrostatic accumulation of charge, in the case of efficient lightning protection, may appear as a series of discharges over the lightning arresters, which periodically follow each other.

b. Electrostatic induction from a passing cloud.

Assuming, for instance, a positively charged cloud passing over a transmission line. The ground below the line then carries a negative electrostatic charge, corresponding to the positive charge of the cloud. The line should have a negative charge also, even higher than the ground, since projecting above it. If the line is insulated from the ground, without the negative charge required for electrostatic equilibrium, it thus appears at a positive

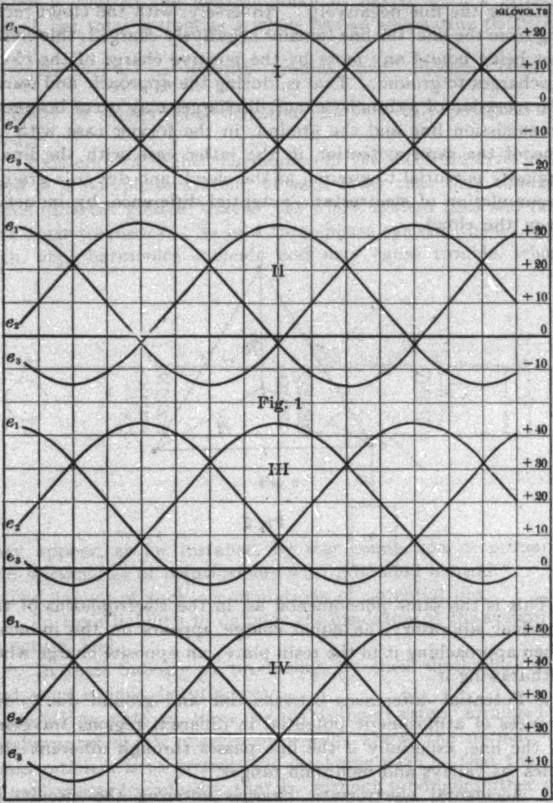

Fig. 1

potential against ground; that is, at cloud potential. With the approach of a positively charged thunder cloud to the transmission line, the positive potential of the line against ground rises until a discharge takes place from the ground to the line, charging the line negatively. Inversely, with the cloud receding from the line, the line remains negatively charged; this charge not being bound any more by the positive charge of the cloud, discharges to ground. That is, during the approach and during the recession of a thunder cloud, discharges may occur between a transmission line and the ground; in the former case with the line of the same potential, in the latter case, with the line of opposite potential to ground, as the cloud, and due to a gradual accumulation of electrostatic potential difference, by induction from the cloud.

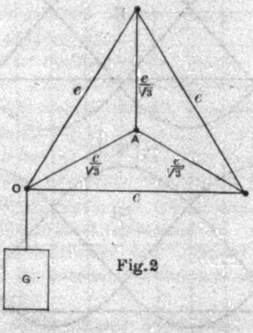

Fig. 2

This is the same phenomenon as, in the electrophorus of the physical laboratory, an equal charge appears on the inductor when approaching it to the resin plate; an opposite charge when withdrawing it.

c. Potential differences between line and ground due to differences of atmospheric potential in different regions traversed by the line, especially if the line passes through different altitudes as valleys and mountain ranges.

d. Accidental electrostatic charges entering the circuit, as friction electricity from the belt of belt-driven machines.

Somewhat similar phenomena result from:

e. Unsymmetrical conditions of the generator potential. For instance, if in a three-phase system one line is grounded, with the three-phase voltage e between the lines (Fig. 3) and $\frac{e}{\sqrt{3}}$ between lines and neutral, the mean potential of the total system is that of the neutral point A, hence, with a ground G at O, the total system as a whole has an alternating potential difference $O\,A = \frac{e}{\sqrt{3}}$ against ground, and induces electrostatically or causes other disturbances, with this potential difference.

f. Existence of higher harmonics in the electromotive force wave of a polyphase system, of such order that they coincide in the different phases; that is, the whole system rises and falls with their frequency. So in a three-phase system, the 3d, 9th, 15th, etc., harmonics coincide and may cause trouble, where they appear, as for instance, by star connection or primaries and secondaries of transformers with grounded neutral.*

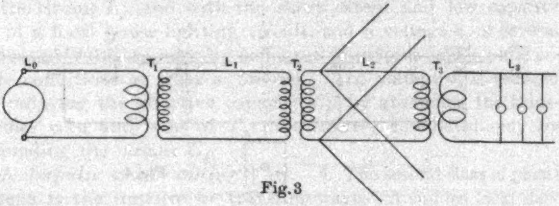

Fig. 3

The danger of such accumulations of potential lies:

a. In their liability to damage the insulation of the system by puncture, and

b. In their liability of producing, by their discharge, other and more serious disturbances.

In taking care of these by lightning-arresters arranged to discharge at a safe margin of voltage above the normal, the main problem is to arrange the discharge path so that the discharge passes harmlessly; that is, without producing other disturbances. It is the same problem as in the protection of a water-power station against freshets by dam and overflow, safely to discharge the water by means of the overflow.

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*See A. I. E. E. Proceedings, November, 1906, Discussion.

3. The effects of steady electrostatic stress, whether unidirectional, *a* to *d*, or alternating as *e* and *f*, appear not only in its own circuit, but also in circuits in inductive relation thereto, and may even be more serious in secondary circuits. For instance, let Fig. 3 diagrammatically represent a transmission system, comprising generating station L_0, step-up transformers T_1, transmission line L_1, step-down transformers T_2, primary distribution circuits L_2, a local lighting transformer T_3, and house light circuit L_3.

All these circuits have capacity against ground, and the transformers also capacity between primary and secondary, and as regards the electrostatic capacity, the system can diagrammatically be represented by Fig. 4.

Let C_0, C_1, C_2, C_3, represent the capacities against ground respectively of the generating station L_0 and the circuits L_1, L_2, L_3 (including the capacities of the corresponding transformer coils against ground) and, C_1', C_2', C_3', the capacities between primary and secondary of the transformers T_1, T_2, T_3.

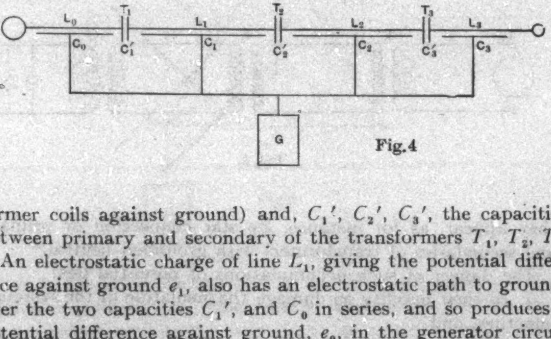

Fig.4

An electrostatic charge of line L_1, giving the potential difference against ground e_1, also has an electrostatic path to ground, over the two capacities C_1', and C_0 in series, and so produces a potential difference against ground, e_0, in the generator circuit L_0, which is intermediate between e_1 and 0, in the proportion of the capacities C_1' and C_0; that is,

$$e_0 = \frac{C_1'}{C_1' + C_0} \tag{1}$$

e_0 is very much lower than e_1, but the circuit L_0 is of very much lower voltage than the circuit L_1, and while e_1 may be a safe voltage for the high-potential insulation of L_1, the lower voltage

e_0 may be beyond the safe limit of the insulation of the low-potential circuit L_0.

If L_0 is a generating station, or sub-station, its capacity against ground, C_0, is so large compared with the capacity C_1', that for steady stress the voltage e_0 is generally negligible, and this phenomenon is appreciable only when e_1 is an alternating potential, or the high frequency of an impulse or oscillation. Hence this phenomenon is of importance only where the capacity of the low potential circuit against ground is small. This may be the case in a house lighting circuit. An electrostatic, or alternating voltage (case *e* and *f*) e_2 in the primary distribution L_2, gives an induced voltage:

$$e_3 = \frac{C_3'}{C_3' + C_3} \tag{2}$$

in the circuit L_3, and with the short extent and low capacity C_3 of a local house-lighting circuit, and a voltage e_2 of several thousand volts, e_3 may be sufficient to involve under unfavorable conditions at least a fire-risk. The voltage e_3 is reduced by reducing the effective capacity C_3' by grounding the transformer core and case of T_3; but entirely eliminated only by grounding the circuit C_3.

2. *Impulse and Traveling Wave.* 4. The second class of phenomena is the impulse or traveling wave. A sudden local electrostatic charge of a transmission line, as by a lightning stroke, or inductively by a lightning flash suddenly discharging a cloud, or any other sudden local change, produces a wave of potential and of current which runs along the line, just as a water wave runs over the ocean surface.

Such a potential wave or impulse is very high and of steep wave-front at its starting point or point of impact, but gradually broadens and flattens out, and ultimately disappears, if the line is of unlimited length; just as the wave produced, for instance, by throwing a stone into a body of water is steepest at the point of impact and gradually flattens out and disappears. Successive stages of such a traveling electric wave are illustrated by Figs. 5 and 6.

Such a wave, when reaching the end of the line, is reflected and thrown back, thus returning again and so forming a system of nodes, and maxima, as shown diagrammatically in Figs. 7 and 8; that is, a standing wave.

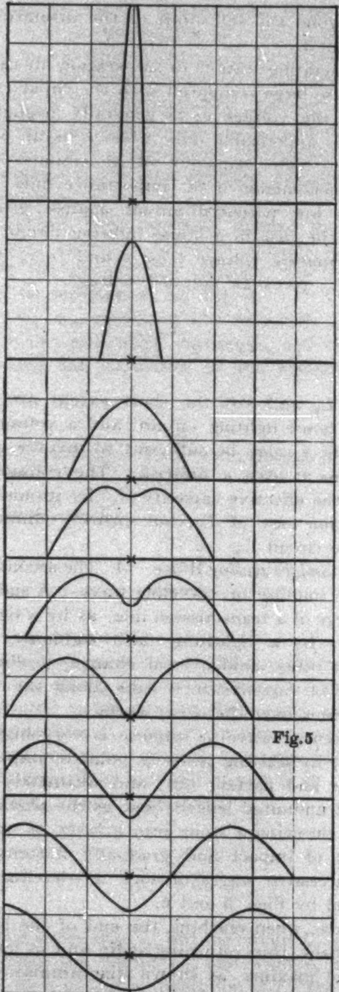

Fig. 5

When reaching the station—generating or sub-station—such a traveling wave is partly reflected by inductance of reactive coils, transformers, instruments, etc., and partly transmitted. The different reflected and transmitted waves so superpose upon

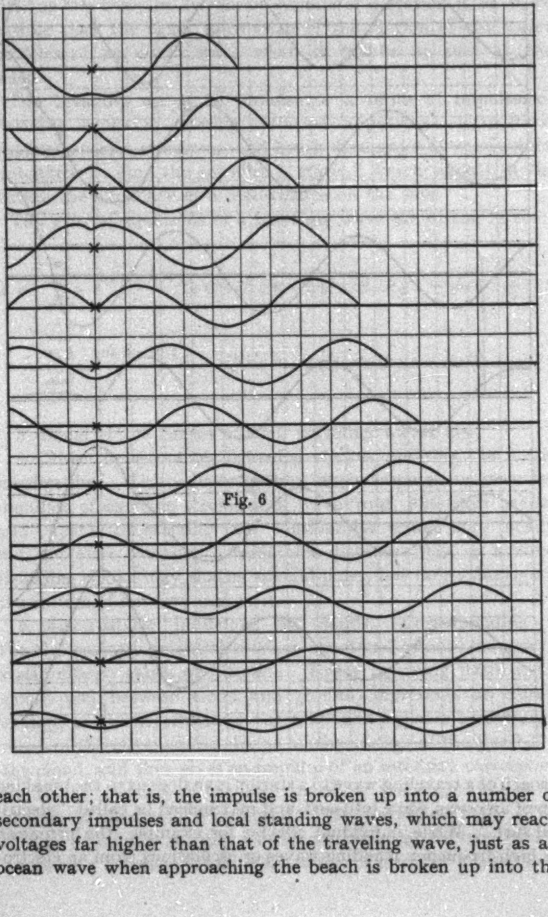

Fig. 6

each other; that is, the impulse is broken up into a number of secondary impulses and local standing waves, which may reach voltages far higher than that of the traveling wave, just as an ocean wave when approaching the beach is broken up into the surf, with wave-crests far exceeding in height that of the unbroken wave.

The complex system of phenomena resulting from the approach of a traveling wave to a station is analogous to the breaking up of an ocean wave into surf, and may indeed be called "electrical surf." While individual effects; for example the formation of high-frequency standing waves or oscillations from an electro-

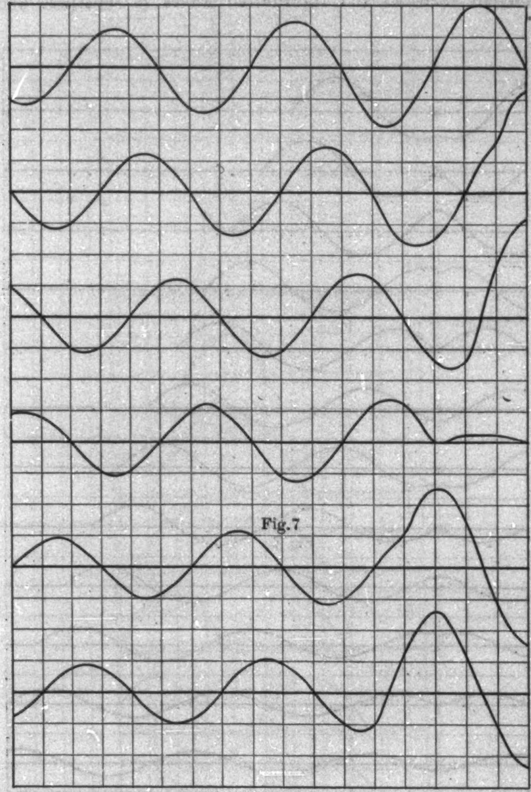

Fig. 7

static impulse entering a circuit of inductance and capacity, the effect of an inductance in the path of an impulse, the phenomena occurring at a branching point between two circuits, etc., can be calculated, the complete predetermination of all the electrostatic and electromagnetic effects of an electric wave entering the complex system of circuits of a station is no more feasible than the exact calculation of the motion of the water particles of an ocean wave when it breaks as surf at the beach.

The breaking up of an impulse or a series of impulses or traveling waves in entering a station appears as electrostatic displays, sparks, streamers, and brush discharges at conductors, switchboards, etc., the so-called "static," which signals in the station the existence of a disturbance on the line.

The general equations of a traveling wave are of the form:

$$\left.\begin{aligned} e &= \sum_{1}^{\infty}{}_{k}\, \varepsilon^{a_k u - b_k t} A_k \cos (k c u - w_k) \cos (k g t - \phi_k) \\ i &= \sum_{1}^{\infty}{}_{k}\, \varepsilon^{a_k u - b_k t} B_k \cos (k c u - w_k') \cos (k g t - \phi_k') \end{aligned}\right\} \qquad 3$$

5. Some of the causes of such traveling waves are:

a. Direct or secondary lightning strokes entering the transmission line. This usually gives a single impulse, or very few impulses of extreme steepness of wave-front, but short extent, and capable of exerting very considerable power only locally, but not after traveling considerable distance; that is, a direct lightning stroke may shatter several poles, but do no damage to the station, if not very near to it.

b. Electrostatic induction by clouds. Corresponding to the electrostatic potential between cloud and ground an electrostatic charge exists on the line. Every lightning flash in the cloud, and between cloud and ground, represents an abrupt change of the electrostatic potential and requires a rearrangement of the electrostatic charge on the section of the line below the cloud, and thus gives an impulse of an intensity corresponding to the intensity of the flash, or rather the magnitude of the change of electrostatic potential of the terrestrial field. Thus during a thunder storm, or other atmospheric electric disturbances near a transmission line, a series of impulses travel along the line, increasing in severity and frequency with the approach, and decreasing again with the recession of the storm. While each of these impulses is rarely of sufficent power to do serious damage, due to their frequency of recurrence, they may lead to the production of destructive internal surges.

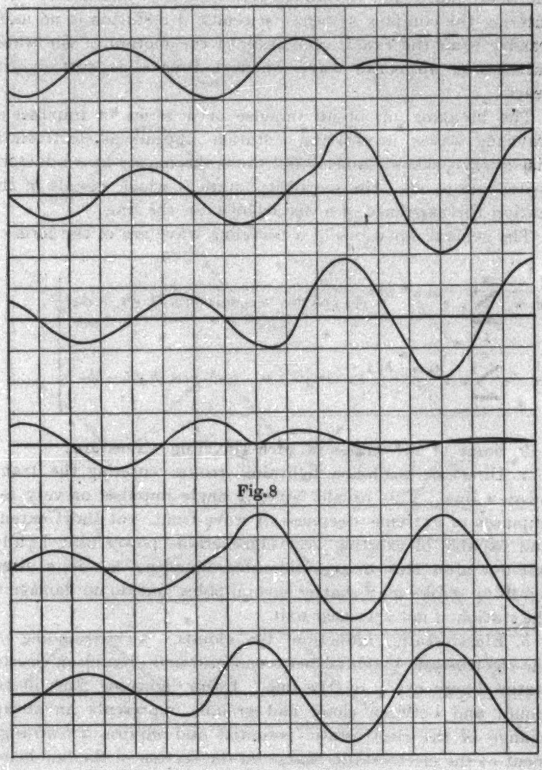

Fig. 8

Traveling waves resulting from this electrostatic induction are usually of lesser voltage than direct lightning strokes, but their origin is of greater local extent; that is, they do not cause local destruction at the point of origin, but travel considerable distances, and their effect is therefore far more generally felt through the system. They probably are the most common manifestation of atmospheric electricity in electric circuits.

Through the electrostatic capacity between primary and secondary of transformers, these impulses frequently enter secondary circuits at an intensity increased by partial reflection at the transformer, and may even lead to sparks jumping from secondary wires to ground, as gas and water pipes, thus constituting a certain fire-risk, which can be completely eliminated by permanently grounding the secondary circuit.

c. Discharges of slowly accumulated potential, resulting in a series of successive impulses.

d. Any spark discharge from the line to another line or to the ground.

e. an arcing ground on one phase of an insulated system, or in general the existence of a " self-rupturing arc " in the system. As explained on former occasions, an arc, when shunted by capacity, as an arc between one conductor of an insulated transmission line and the ground, or between a conductor and the armor of an underground cable, is self-rupturing; that is, blows itself out explosively, due to the characteristics of the arc, and hence produces an impulse. An arcing ground thus sends out a series of impulses. Due to the very rapid succession and considerable power—the $\frac{e^2C}{2}$ of the system—these impulses are very serious electric disturbances of the system, and frequently lead to a low-frequency surge and result in extensive destruction. In their appearance in the station, they are very similar to *b* except of greater intensity and rapidity, and therefore are more dangerous.

f. Sudden changes of load, connection and disconnection of apparatus, etc., also cause impulses. For instance, when connecting a dead transformer to the system an impulse traverses the transformer, and usually penetrates beyond the transformer into the circuit.

3. *Standing waves, oscillations, and surges*. 6. In water, standing waves are less frequent and prominent appearing in general only as stationary ripples in small pools. They form when a wave-train is reflected and thrown back by an obstruction, and the returning wave and the incoming wave

meet. Then at some places the waves neutralize each other and form a node; at others they add to a wave-crest of greater height than the traveling wave. Figs. 5 to 8 show the gradual change from an impulse to a traveling wave-train, and from the traveling wave to the standing wave or oscillation. Wave formation takes place only in large bodies of water, in which the wave-length is small compared with the total path of wave-travel, and the boundary usually too irregular to give good reflection and to allow standing waves to form. Standing waves, however, are the vibration of a tuning fork, or a violin string, or of the air in an organ pipe. Since the velocity of propagation of an electric wave is very high, 188,000 miles per second, even with very long transmission lines, oscillating as a single standing wave, or at fundamental frequency, the period of oscillation is relatively short, the frequency hundreds of cycles per second. In this respect, an electric circuit is rather more analogous to a violin string or the body of air in an organ pipe, and has the same tendency to form regular standing waves or oscillations. Just like a violin string, the electric circuit may oscillate either as single wave without nodes, or a number of nodes form, and the different sections oscillate separately, at higher frequencies.

This phenomenon of standing waves, or oscillations in transmission lines, has been investigated repeatedly. It is usually approached by considering the distribution of current and potential in a circuit of distributed capacity, inductance, and resistance.*

The standing wave is produced by the superposition of a wave and its reflected wave, and the general equations result from equation (3) by combining the impulse with the reflected impulse. Since the production of an oscillation or standing wave presupposes a slow decay of the wave-train; that is, b_k must be small, an approximate value is derived by suppressing the term $\varepsilon^{-b_k t}$. This means neglecting the gradual dying out of the wave; that is, considering it as alternating instead of oscillating. The trigonometric function of time can then be eliminated by the introduction of the complex quantity, and the equation of the standing wave, or oscillation, becomes:

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*See Steinmetz, Alternating Current Phenomena, third edition, page 181.

$$E = \varepsilon^{-r\sqrt{\frac{\pi}{2}\frac{C}{L}}\,u} \sum_1^\infty k\, A_k \left(\cos \frac{k\,\pi\,u}{2} + j\,k \sin \frac{k\,\pi\,u}{2}\right)$$

$$- \varepsilon^{+r\sqrt{\frac{\pi}{2}\frac{C}{L}}\,u} \sum_1^\infty k\, B_k \left(\cos \frac{k\,\pi\,u}{2} - j\,k \sin \frac{k\,\pi\,u}{2}\right) \qquad (4)$$

$$i = \sqrt{\frac{C}{L}} \left\{ \varepsilon^{-r\sqrt{\frac{\pi}{2}\frac{C}{L}}\,u} \sum_1^\infty k\, A_k \left(\cos \frac{k\,\pi u}{2} + j\,k \sin \frac{k\,\pi u}{2}\right)\right.$$

$$\left. + \varepsilon^{+r\sqrt{\frac{\pi}{2}\frac{C}{L}}\,u} \sum_1^\infty k\, B_k \left(\cos \frac{k\pi u}{2} - j\,k \sin \frac{k\,\pi\,u}{2}\right)\right.$$

where:

L = inductance,
C = capacity,
r = resistance,
per unit length of line, and
A_k and B_k are complex constants.

The lowest frequency of oscillation of a line is the frequency which makes the line a quarter wave-length. That is, if:

l = length of line,
v = velocity of light,
It is:

$$N_0 = \frac{v}{4\,l} \qquad (5)$$

$$= \frac{47000}{l}$$

If l is given in miles.

From the line constants this fundamental frequency can be expressed, approximately, by:

$$N_0 = \frac{1}{4\sqrt{L_0\,C_0}} \qquad (6)$$

where:

$L_0 = l\,L$ = total inductance,

$C_0 = l\,C$ = total capacity of the line.

In addition to the fundamental frequency L_0, all its odd higher harmonics, or any frequency:

$$N = (2\,k - 1)\,N_0 \qquad (7)$$

may exist.

7. In general, an oscillation of a transmission line is a complex wave, containing fundamental and higher harmonics. The relative proportions of the different harmonics in the oscillating wave depend upon the distribution of potential and of current at the moment of the start of the oscillation.

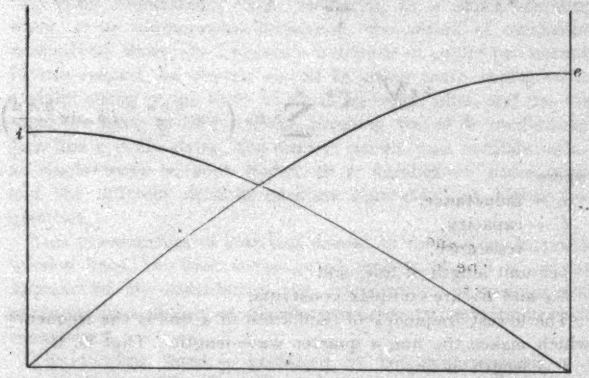

Fig. 9

If the distribution of potential and of current at the start of the oscillation were perfectly sinusoidal, as shown by Fig. 9, only the fundamental wave would appear. The more irregular the distribution is, the more prominent are the higher harmonics; with a very irregular and abrupt distribution, the fundamental wave does not appear at all, but only higher harmonics.

A transmission line has, therefore, not only one frequency of oscillation, as a combination of condenser and separate inductance, but an infinite number of frequencies, of which one is the lowest or fundamental, the others its odd multiples or higher harmonics.

These frequencies depend on the resistance, inductance, and capacity of the line. None of these quantities is entirely constant. For instance, at high voltage the capacity increases by electrostatic glow, brush discharges, and streamers; inductance and resistance vary with the unequal current distribution throughout the section of the conductor, etc., so that at the very high harmonics, which are close together—for instance, the 199th and the 201st harmonics differ in frequency by 1% only—the gap between successive harmonics is bridged by the variability of the frequency, and a line for very high frequencies can thus oscillate at any frequency whatever. In other words, a transmission line can oscillate at a fundamental frequency, the lower higher harmonics thereof, and at any very high frequency whatever; that is, the line has definite frequencies of oscillation only at low and moderate frequencies, but not at very high frequencies. This is analogous to the formation of other standing waves.

8. The oscillation is the phenomenon by which in an electric circuit after a disturbance of the circuit conditions the flow of power restores its equilibrium. Any circuit disturbance may, and usually does, produce an oscillation which may be local only, that is, contain only the very high-frequency harmonics, if the disturbance is local; but it may become universal by including the fundamental and the lower harmonics. In the latter case it is usually called "surge."

In some respects, therefore, the oscillation is a result of a disturbance, as an impulse, and the power which oscillates is the generated power of the circuit; hence the possible destructiveness of the oscillation is limited only by the available power of the generating system, but does not directly depend upon the severity of the disturbance which caused the oscillation.

The power, which oscillates, is the energy stored by the flow of generated power in the electric field of the transmission line, as electromagnetic energy: $\frac{i^2 L}{2}$, and as electrostatic energy: $\frac{e^2 C}{2}$, and the shorter the section of line which oscillates the higher is the frequency of the oscillation. The smaller, however, is also the power and the destructiveness of the oscillation; considerable damage results, therefore only from low-frequency oscillations; that is, oscillations of the whole or a large part of the system. Local high-frequency oscillations are dangerous chiefly in their liability to destroy insulation by puncture, and to produce a low-frequency surge of higher power.

Since as a rule the maximum amount of energy which can be stored in the electric field of a circuit is the electromagnetic energy of the short-circuit current, $\frac{i_0^2 L}{2}$, the short-circuit surge is the most powerful and destructive.

Some typical forms of oscillations are:

a. Spark discharges to and from the line, as over some lightning-arresters; the breaking up of a traveling wave when entering the station, etc., result in the formation of very high frequency oscillations, millions of cycles per second.

b. Arcing grounds and other arc discharges to ground from a line of an insulated system; reflected traveling waves, etc., give oscillations which, while still of very high frequency, reach considerably further down in frequency than *a*, hundred thousands of cycles per second, and still lower.

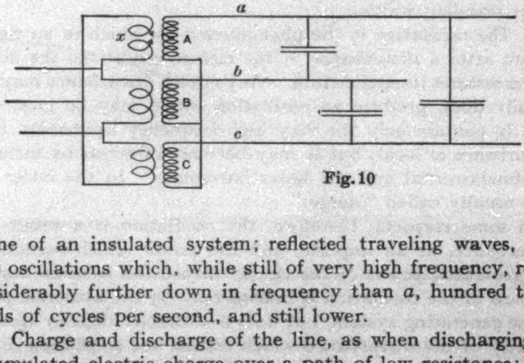

Fig. 10

c. Charge and discharge of the line, as when discharging an accumulated electric charge over a path of low resistance; connecting a dead transformer into the circuit, etc., results in high-frequency oscillations containing also an appreciable low-frequency component.

d. In general, changes of circuit conditions, as sudden changes of load; connecting or disconnecting a transmission line; opening a short circuit suddenly, etc., give oscillations in which the fundamental frequency predominates.

e. Low-frequency surges, consisting primarily of the fundamental wave, may be produced by certain transformer connections in polyphase systems, in which in case of an accident, an unequal distribution of load, or other causes, the open circuit inductance of a transformer coil is in series with the line capacity, in the circuit of a live transformer. Typical hereof is the case of a delta-star connected system without grounded neutral, if one of the sides of the delta is open circuited, as shown as X in Fig. 10. The high-tension coil A of this transformer is in series with the line capacity, $a-b$, in the circuit of transformer B, and in series with the line capacity, $a-c$, in the circuit of transformer C. In this case the voltage between a and the other two lines b and c is practically unlimited. A number of such transformer connections exist, and in their use this phenomenon should be guarded against.

9. Looking at the oscillation as surge of energy between the electromagnetically stored energy, $\frac{i^2 L}{2}$, and the electrostatically stored energy, $\frac{e^2 C}{2}$, it can well be seen, that the electrostatic energy is in general far more limited than the electromagnetic energy; and the maximum possible energy which can be stored in the electric field is the electromagnetic energy of the short-circuit current, as stated above. The most powerful oscillation is therefore the short-circuit surge of a system or oscillation produced by instantaneously rupturing a short circuit, as by a self-rupturing arc. In this surge the fundamental predominates, and the equations of the surge potential are:

$$e = i_0 \sqrt{\frac{L}{C}} \left\{ 1.26 \cos \omega \sin \phi + 0.40 \cos 3\omega \sin 3\phi + 0.22 \cos 5\omega \sin 5\phi + 0.13 \cos 7\omega \sin 7\phi + 0.07 \cos 9\omega \sin 9\phi + 0.03 \cos 11\omega \sin 11\phi + \ldots \right\} \quad (8)$$

where:

i_0 = short-circuit current
L = inductance of line
C = capacity of line

$$\omega = \frac{\pi u}{2 l} \quad (9)$$

l = length of line,
u = distance along line, from point where the short circuit was ruptured, as zero point.

$$\phi = 2 \pi N t \quad (10)$$

t = time

$$N = \frac{1}{4\sqrt{L\,C}} = \text{frequency of fundamental wave of oscillation.} \tag{11}$$

For instance, for a line of 50 miles, consisting of wire No. 0000, and transmitting 30,000 volts at 25 cycles, it is, approximately:

$L = .2\,h$, hence:
$x = 2\,\pi\,N_0\,L = 31.4$ ohms
$C = 0.4$ mf., hence:

$$N = \frac{1}{4\sqrt{L\,C}} = 880 \text{ cycles}$$

$$\sqrt{\frac{L}{C}} = 707$$

$r = 26$ ohms,
hence:

$$z = \sqrt{r^2 + x^2} = 40.8 \text{ ohms},$$

and, assuming that the supply voltage, with a short circuit at the other end of the line, drops instantly to one third, or $e_0 = 10{,}000$ volts:

$$i_0 = \frac{e_0}{z} = 245 \text{ amperes.}$$

hence the surge voltage:

$$e = 174{,}000 \quad \{1.26 \cos \omega \sin \phi + 0.40 \cos 3\,\omega \sin 3\,\phi + 0.22 \cos 5\,\omega \sin 5\,\phi + \; . \; . \; . \} \text{ volts.}$$

At:

$$i_0 = 245 \text{ amperes,}$$

this gives the power of the oscillation:

$$e\,i_0 = 42{,}500 \text{ kilovolt-amperes.}$$

Standing waves or oscillations in electric circuits vary from the very low frequency of the fundamental surge of very long transmission lines, which approaches commercial alternating-current frequencies, especially when, as commonly is the case, the generating system participates in the oscillation, to frequencies of several hundred million cycles per second, in the discharge oscillation between the cylinders of a multi-gap lightning-arrester. Due to this enormous range of frequency, the physical effect of the oscillation also varies greatly. In very high frequency oscillations the power is very small; the electrostatic effects, as luminous glow, brush-discharge, streamers, and sparks, are prominent, but the direct damage is usually insignificant, and the effect local. Inductance opposes a fairly effective barrier. On the other extreme, low-frequency surges show little or no luminous display; inductance offers no obstruction, but due to their high power and wide extent, considerable damage may be done all over the system.

Oscillations, therefore, are frequently subdivided into high-frequency oscillations, in which the lower harmonics are absent, and low-frequency oscillations, in which the fundamental predominates, The name surge is frequently applied to denote the latter.

Between these two extremes, however, the low-frequency surge and the high-frequency oscillation, oscillations of intermediate frequency are found—against which inductances do not give sufficient protection—which have considerable power, and also give luminous displays, as streamers and brush discharges. Oscillations of this intermediate class are occasionally given by arcing grounds, spark discharges through defective joints in large cable systems, etc.

10. The four types of lightning disturbances here discussed—static charge, impulse, oscillation, and surge, may occur singly, in groups, or all occur together, or rather successively, the one preceding and causing the other. A static charge, for instance, rises, until it breaks through to ground and discharges, thus producing an impulse or traveling wave.

A traveling wave breaks at a station, and produces high-frequency oscillations.

A high frequency oscillation, puncturing the insulation, causes a short circuit, which ruptures itself, and thus produces a low-frequency surge.

A static charge, discharging over lightning-arresters with insufficient damping, causes a high-frequency oscillation.

A static charge, short circuiting the system by its discharge, causes a low-frequency surge.

Lightning-arresters, when discharging a high-frequency oscillation, may fail to hold back the machine current, and the short circuit resulting therefrom produces a low-frequency surge.

All four types of disturbances may occur successively:

An electrostatic charge rises until it breaks down to ground, thereby starting an impulse. This impulse at the entrance to a station breaks up in high-frequency oscillations. These oscillations puncture the insulation and produce a short-circuit surge.

The traveling wave produced by connecting a cable to the bus-bars may cause a spark discharge from conductor to cable armor at some defective joint. This spark develops into an oscillating arc, which sends out traveling waves along the cable. These, when entering the station, produce high-frequency oscillations, and systems of such oscillations follow each other with great rapidity, produced by the successive impulses caused by the oscillating arc, and produce a continuous "static" in the station, which ultimately produces somewhere a short circuit, and consequently a low-frequency surge.

In short, the number of combinations of such phenomena is unlimited.

11. The problem of lightning protection then is threefold.

1. Prophylactic; to guard against the entrance or origin of disturbances.

2. Restrictive; to guard against a disturbance leading to other disturbances.

3. Curative; to discharge a disturbance harmlessly:

As seen, the problem is a vast one, and comprises nearly every part of design, installation, and operation of the system.

1. Prophylactic; against entrance of atmospheric disturbances The location of the transmission line should be chosen so as to avoid exposed positions as far as possible. A grounded overhead wire of good conductivity offers considerable protection. Grounded side wires increase the protection and discharge side drift. The question of barbed wire against plain wire is still open to discussion. Emergency arresters in the lines or arresters at intermediate stations may shunt traveling waves toward ground.

Grounding the neutral of the high-potential circuit offers some protection against static charges and against arcing grounds, but increases the liability to short circuits and shutdowns due ot other causes.

A study of transformer connections and their operating conditions, of generator wave-shape and connections, of the possible origin of higher harmonics of the potential wave, the construction and location of underground cables, the protection of their joints, the desirability, size and location of reactive coils—all are subjects requiring careful consideration from the point of view of lightning protection. In short, the most important problems of lightning protection are met and should be solved before the question of lightning-arresters is approached.

The problems 2 and 3, to limit the disturbance, so that it does not cause other and possibly more severe disturbances, and to discharge it safely, are the problems which the designer of the lightning-arrester has to solve.

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[illegible]

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1. [illegible]

2. [illegible]

3. [illegible]

4. [illegible]

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A paper presented at the 217th meeting of the American Institute of Electrical Engineers, New York, March 29, 1907.

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PROTECTION AGAINST LIGHTNING, AND THE MULTIGAP LIGHTNING ARRESTER

BY DAVID B. RUSHMORE AND D. DUBOIS

In this paper the term "lightning" is used in its comprehensive sense as defined by Dr. Steinmetz to include "All phenomena of abnormal voltage and abnormal frequency."

The object of this paper is to set forth the most recent developments in the multigap lightning arrester and to give recommendations concerning the protection of transmission lines and electrical apparatus from lightning disturbances. Reliable photographs of lightning are rare and difficult to obtain. A number of these, some of which have been published before, showing the varieties of lightning discharge, are included as a matter of general interest.

Fig. 1 is an instantaneous exposure of a stroke showing the peculiarly knotted path often taken. The best explanation of this is that the lightning at that point took a direction toward the camera, and, as is always the case, did not follow a straight line. We, of course, see the projection of its path in our direction.

Fig. 2 shows an instantaneous photograph of what is known as a meandering discharge. It is confined to the clouds and seems to be a general neutralizing of potentials.

Fig. 3 is an actual photograph of that riddle, "the thunderbolt." This phenomenon has been observed so often that we cannot deny its occurrence. There are at least three theories as to its nature.

1. That it is what it appears to be, a ball of globular lightning, which bounds about burning and destroying. This theory is backed up by no explanation.

2. That it is an optical illusion. That the eye is blinded by the light of a lightning flash and therefore sees the ball of fire wherever it looks. This theory is rational except that it does not account for the damage done where the ball is last seen.

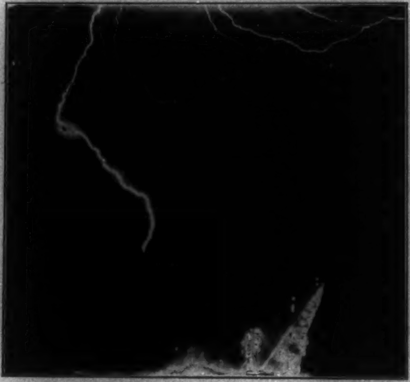

Fig. 1.

Fig 2.

3. That the eye sees a stroke coming directly toward it from the sky, as in the knot of Fig. 1. This would produce the effect

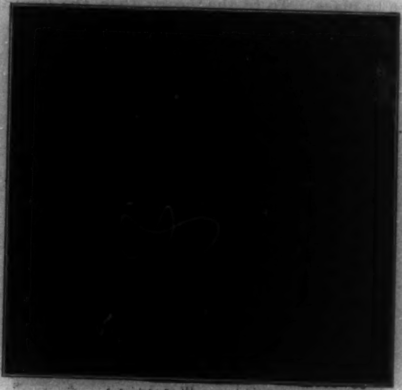

FIG. 3.

FIG. 4.

of a ball of fire, but the ball described usually moves slowly from place to place. To fit the theory, then, the lightning must be supposed to last for a considerable time and to shift its path, or to be made up of a number of strokes, each traveling by a slightly different path.

FIG. 5.

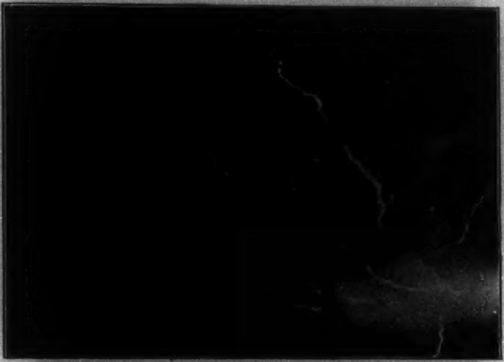

FIG. 6

The photograph here shown should discredit the second of these theories. The dotted character of a part of a stroke should be noted.

Fig. 7.

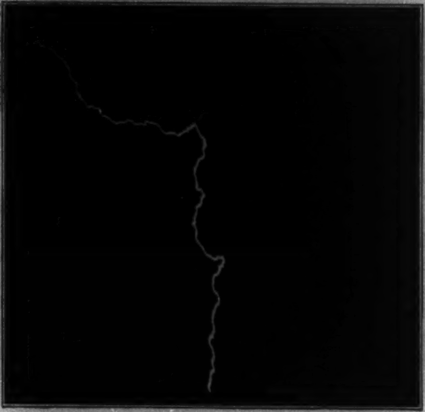

Fig. 8.

Fig. 4 shows in the lower corner another of these peculiar strokes.

Fig. 5 shows what is known as ribbon lightning. This photograph was taken from an express train on the prairie of North Dakota. This effect may not be due to the movement of a camera, as the telegraph pole shown shows no movement. It may be, however, that only the brightest part of a flash gave enough light to take the photograph of the pole. In the first case we would conclude that the stroke moves sideways. In the second case that the stroke lasted for some time. Possibly if viewed from near the point of striking this would have resembled the "thunderbolt" of Fig. 3.

FIG. 9.

Fig. 6 shows a radial discharge among the clouds.

Fig. 7 shows a parallel discharge, most likely two discharges, one closely following the other.

Fig. 8 shows a horizontal discharge turning earthward. In this case a discharge must have started from cloud to cloud, but have come so near the earth that a second and stronger stroke took place from earth to one of the clouds. The second stroke would naturally follow the path ionized by the first.

Fig. 9 shows a horizontal discharge from cloud to cloud over Salt Lake City.

Fig. 10 is a remarkable photograph of lightning striking the tower of the City Hall in Philadelphia. This stroke knocked off one of the great iron rosettes of the tower but did no great damage.*

In considering lightning protection, the first step is naturally to study the apparatus to be protected, then the forces to which it will be subjected, and finally the protecting apparatus. The source of trouble "Lightning" is the subject of another of this evening's papers. For apparatus to be protected, we have insulators, transformers, switches and generators. The specifications for dielectric strength of generators is as provided for by the American Institute of Electrical Engineers. The usual specification for high-tension transformers is that they shall stand from line to core twice the normal line voltage, independently of whether the transformers are star or delta connected. Switches are made to stand two and one-half times normal line voltage, and insulators should stand three times the line voltage dry, and one and one-half times the line voltage

FIG. 10.

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with a precipitation of one-fourth inch per minute at 45°. The allowable rise of potential on the line is therefore less than 100%; about 60% of line voltage seems a desirable point at which the protective apparatus should operate.

Protecting apparatus consists briefly of lightning arresters, horn arresters, static discharges, choke-coils, and ground wires. Here lightning arresters are defined as apparatus that can relieve the line of high voltage without disturbing operating conditions.

Transformer Connections. From the standpoint of protection of the system from static disturbances, whether external or internal, the grounded star transformer connections with overhead ground wire offers the best conditions, and is in general recommended where other conditions do not decide. The causes of most frequent disturbances on transmission systems are short-circuits and grounds.

As regards short circuits between wires, there is but little to choose between the star and delta connections; but as regards grounds, and especially partial grounds, the grounded star system affords a great advantage in the reduced possibility of a disastrous increase in voltage.

When a ground is formed on one line of a high-tension transmission, that line should at once go out of operation, and with a properly designed system no interference with the delivery of power should result.

All of the considerations which enter into the question of transformer connections are not pertinent to the question of lightning protection, but from that standpoint the grounded star system with the overhead ground wire is most desirable.

The Horn Lightning Arrester. Due to its apparent simplicity, the horn lightning-arrester has of late received considerable attention. It is, however, not a piece of real protective apparatus in the sense of protecting the line without disturbing the conditions of operation. If it is used without resistance, it has the effect of a short-circuit; with resistance high enough to prevent it from causing a great drop in voltage, the protective features are largely eliminated. It is in reality an emergency device, a weak point in the system which is the first to rupture when the voltage rises to a dangerous value; if the system is without protective apparatus, it locates the point of breakdown when the condition is such that some failure must occur.

In general, the discharge of horn arresters without resistance will throw synchronous apparatus out of step, and necessitate starting up the system again. The voltage will drop to zero at a short circuit, and, as the arc may last from two to three seconds, the disturbance of the system is considerable. Where a fuse is used in series with a horn having no resistance, it can, of course, take but the one stroke and after this the system is unprotected. A flaming arc in air, such as occurs with the horn arrester, is a possible source of disturbance much worse than the original one, and under certain conditions can give rise to very high voltages, so that the possibility exists that the horn, instead of being a protective feature, may become a disturbing one.

The horn arrester with sufficient resistance to prevent short circuiting the system at time of discharge has some small protective value, which can easily be determined by the amount of resistance used. The real function of the horn arrester is its use to protect insulators along a transmission line, where the horns are so arranged that the current will jump to the horn before it will arc around the insulator. In this case the system would be disturbed either way. Where it is allowed to arc around the insulator, the latter would probably be destroyed and the time of disturbance of the system might be considerable—possibly until the insulator is replaced. With a horn protecting the insulator, the resulting short-circuit, while very undesirable in itself, is less disastrous than in the former case, and may only necessitate starting up the synchronous apparatus again.

Many disturbances caused by atmospheric lightning are of such high frequency that they will not travel along the line for any distance; but will jump to ground within a short distance of where the disturbance originates. To protect against this, the use of horns is recommended.

Care must be taken in the formation of the horns, and it must be remembered that the magnetic effect in putting out the arc is much greater than that of the heat causing the arc to rise. By improperly forming the horns, the arc will travel down instead of up, and will not clear itself. Horn lightning arresters have been installed on transmission lines in this country for a considerable number of years. In most places, however, where they have been used no careful record has been kept of their operation.

Protection for Wood Pole Transmission Lines. Practically complete protection for wood pole transmission lines can be effected against disturbances from atmospheric lightning. The best method of doing this is shown in Fig. 11. Here we have an overhead ground wire in connection with a lightning-rod and

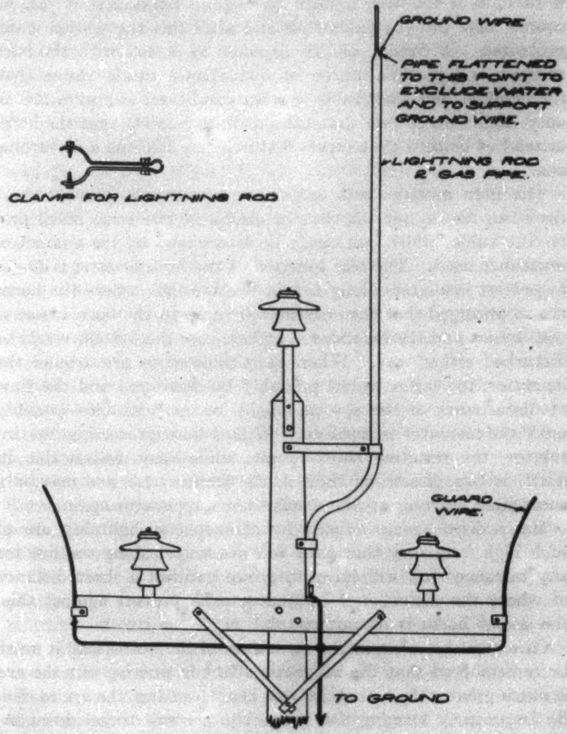
GROUND WIRE
PIPE FLATTENED TO THIS POINT TO EXCLUDE WATER AND TO SUPPORT GROUND WIRE.
LIGHTNING ROD 2" GAS PIPE.
CLAMP FOR LIGHTNING ROD
GUARD WIRE.
TO GROUND

Fig. 11.

horns protecting the insulators. The overhead ground wire relieves the electrical stresses that would otherwise be thrown on the transmission line. The pipe supporting the ground wire acts as a lightning rod, and also as a horn to the top conductor,
)

protecting its insulator. Side horns are attached to the cross-arm, protecting the two lower insulators, and these are all well grounded by a conductor attached to the side of the pole. This sketch is somewhat diagrammatic. The actual dimensions and construction as shown would not be used. The addition of the lightning rods has in some cases been found very efficacious.

Static Discharges. From the description of the new form of multigap arrester it will be seen that the arrester includes a static discharger consisting of the high resistance with the smallest possible number of gaps in series. This should offer sufficient protection against static wherever the arrester is used. There are cases, however, where the complete arrester is not thought necessary; such, for instance, as to protect underground cable systems having no exposure to lightning. In these cases the high resistance and series cylinders can be installed alone. Of course no protection against low-frequency surges of power is obtained, and if such are likely to occur the whole of the arrester should be used.

Water-Jet Arrester. What is known as the water-jet arrester has been used abroad to some extent, and in certain localities has apparently obtained a reputation which it is difficult to justify.

The equivalent needle-gap and the resistance of this arrangement are so great that it is evident that no real protection is obtained by its use. Its only function can be that of a high resistance connected permanently to the line, and in this case it has the advantage of being self-repairing if ruptured by discharge. It should to some extent prevent the slow accumulation of static charges on the line. It is, however, difficult to install, and it is questionable if the same results cannot better be obtained in other ways. Its use is not recommended.

Ground Wire. Without doubt an overhead ground wire affords protection to a transmission line. This protection is not complete, as a very few cases exist where insulators have been lost by lightning strokes even when a ground wire was used, but these instances are so very rare that the use of a ground wire is strongly recommended. It should, however, be installed in addition to other apparatus, and, while it will almost entirely protect the line, it does not protect the station apparatus completely. The use of a ground wire very greatly relieves the stress which can be thrown on the station apparatus, however, and much reduces the duty required of the station lightning arresters.

A ⅜-in. stranded steel wire, grounded at least every 500 ft., should be installed above the highest transmission wire. Experience demonstrates that this is desirable, and that a ground wire below the transmission wires or in the center of a triangle is not as effective as one above. One ground wire is all that is necessary, although theoretically more are better; but, considering the great relief obtained from one wire and the small possible margin of protection from an additional wire, which would double the cost of installation, it is doubtful if commercial considerations would often allow the installation of more than one wire. The ground wire in connection with the earth forms a short circuited secondary which helps to dampen out disturbing oscillations.

Some early experience with ground wires were with those mechanically weak, and, at least in one case, the benefits which might have been derived from the electrical protection were more than cancelled for by the frequent breaking of the wire and the trouble caused by these disturbing the transmission system. With the wires specified above, no such trouble will result.

Where a ground wire is used in connection with the grounded neutral of a star-connected high-tension system, the best results will be obtained. In some cases the ground wire is mounted on insulators and is identical with the other conductors, in which case it is possible to use it as a spare conductor after removing the grounds. In all cases, both with wooden pole transmission lines and where steel towers are used, the use of a ground wire is recommended as a protective device against the effect of lightning.

Choke-Coils. The disturbances on a system in which protective apparatus is used come from various sources and are of various characteristics as regards voltage and frequency. If our object was to protect the station against disturbances which emanate from the transmission line, high reactance might be desirable except as it interferes with the regulation of the system. When, however, the disturbance is inside the choke-coil, high reactance is undesirable. In the case of a system with large capacity, an arcing ground in series with the high-reactance choke-coil may cause excessive rise of voltage. If one goes through the list of possible disturbances, it is seen that in some cases high reactance in a choke-coil is desirable; in others it is equally undesirable. It is, therefore, recommended that a choke-coil be used, but that it possess but moderate reactance, sufficient to reduce the pressure thrown on the station apparatus by an amount which will in general bring it within the safe value of the dielectric strength of such apparatus. Moreover, a choke-coil to be effective at high-frequency discharges should have very little capacity between turns; otherwise the discharge will merely pass through from turn to turn. The coils should, therefore, not be too close together and should be insulated by a substance having low specific inductive capacity—air. Another advantage of air as an insulator for a choke-coil is that there is no chance of permanent short circuit. Where ordinary insulation is used in a choke-coil there is no way to tell that the insulation has not been destroyed. Each stroke may break down a few turns until finally the coil is punctured from end to end. At the next stroke there is trouble.

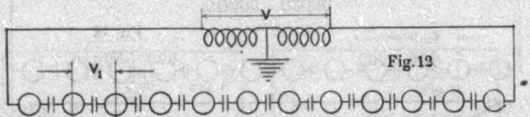

Fig. 12

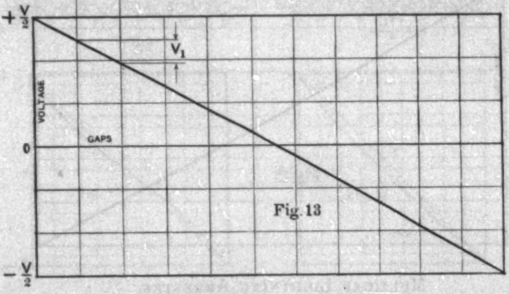

Fig. 13

Grounds. It is of the utmost importance to have lightning arresters well grounded. The ground wire, preferably flat copper strip, should lead directly to ground with as few bends as possible. It sometimes happens that a good ground cannot be conveniently made near the arrester, or that a better one can be made at a more distant point. In this case it is recommended that the principal ground be made at the more distant point, but that a ground of some sort, the best possible under the conditions, be made directly underneath the arrester. By the use of three grounds at a station the ground resistance of each can be determined. The two secondary grounds need not be complicated or expensive; iron pipes driven into the ground will answer. A record of the resistance of the grounds can thus be kept, and their good condition assured. All three should be used in parallel.

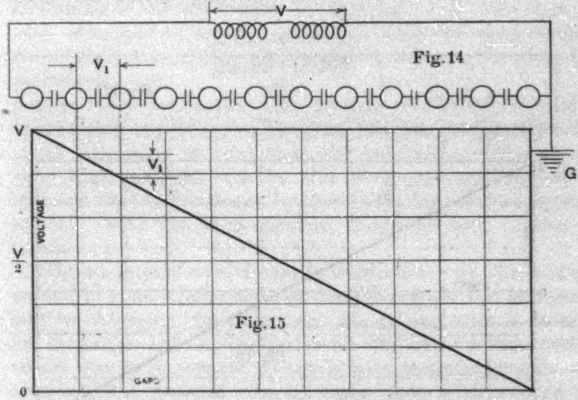
Fig. 14

Fig. 15

MULTIGAP LIGHTNING ARRESTER.

Theory. As is well known, the essential elements of the multigap lightning arrester consists of a number of cylinders between line and ground and line and line, these cylinders being spaced with a small air-gap between them.

The multigap arrester is distinguished from the single-gap arrester in that it can be made to discharge abnormal rises of potential without disturbing operating conditions. Under most conditions of operation, it discharges at a much lower voltage than does a single gap the length of which is equal to the sum of the small gaps, and the interrupting power is such that the disturbing charge passes off without allowing the dynamic current to follow for more than one-half cycle.

The following theory of the multigap arrangement is in part new, and is the result of very careful study of its characteristics.

As shown diagrammatically in Fig. 12, the cylinders of the multigap arrester act as plates of condensers in series. This condenser function of the multigap arrester is the essential feature in its operation.

Supposing capacity to exist between the cylinders, and no capacity between cylinders and ground; if a potential is applied across the arrester, the distribution of this potential will follow a straight-line law and the fall of potential will be the same between any two cylinders. This is shown in Fig. 13. If now we ground one end of this device, Fig. 14, the distribution of potential over the cylinders remains the same in value, but the potential is all in one direction, or the whole device is raised above zero potential, as shown in Fig. 15. However, besides the capacity between cylinders, capacity also exists between each cylinder and ground. This is shown diagrammatically in Fig. 16. The function of this second capacity is to distort the gradient.

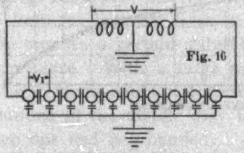

Fig. 16

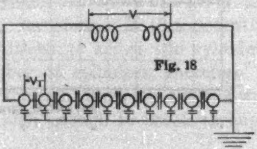

Fig. 18

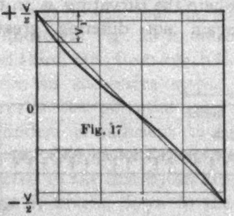

Fig. 17

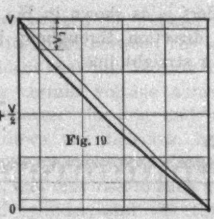

Fig. 19

Where the number of cylinders is small, the curve showing the distribution of potential does not differ greatly from a straight line, as shown in Fig. 17. It will be noticed that this is a reversed curve, being symmetrical above and below the line of zero potential.

If instead of grounding the transformer in the middle, we now ground it at one end, (Fig. 18), the whole device is raised above zero potential and the distribution of potential over the cylinders is as shown in Fig. 19, where the curvature is in the same direction throughout but again not differing greatly from a straight line.

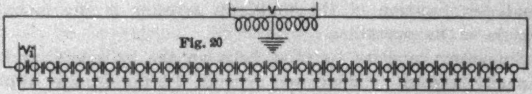

Fig. 20

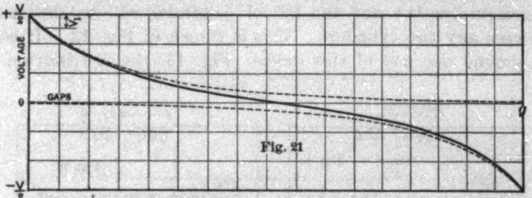

Fig. 21

POTENTIAL GRADIENT, UNGROUNDED

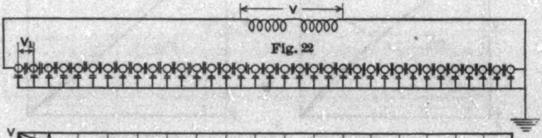

Fig. 22

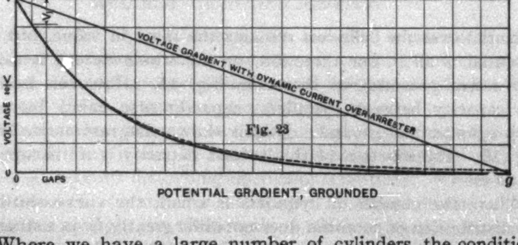

Fig. 23

POTENTIAL GRADIENT, GROUNDED

Where we have a large number of cylinders, the conditions are somewhat changed. If we have a device as shown in Fig. 20, which is supposed to represent a large number of cylinders connected across a transformer with grounded neutral, the distribution over which is shown in Fig. 21, it will be noted that this curve differs considerably from a straight line. In this case there is a part of the apparatus in the middle where very small difference of potential exists between the cylinders, and the fall of potential at the end cylinders is much greater than that which exists between the cylinders nearer the middle. The distribution of potential over the device exhibits the general form of combination of an exponential function of opposite sign. If one end of the transformer is grounded instead of the middle, as shown in Fig. 22, we have the distribution of potential shown in Fig. 23. It will be noted that the drop of potential over the end cylinders, as shown in V_1, Fig. 23, is very much greater than that shown in V_1, Fig. 21, the voltages between lines being the same. If this potential drop reaches a certain value, a discharge across the cylinders takes place. With a large number of cylinders, therefore, a voltage which could not break through when the system was grounded in the middle may be high enough to break through when one end is grounded.

It will be seen that the potential between the first and second cylinders in Fig. 23 is much greater than between the second and third, etc., from which it is evident that this arrester breaks down in successive steps. At a certain voltage across the arrester the potential gradient between the first and second cylinders is sufficient to break down the dielectric between them. The potential of the second cylinder, then, being connected to the first by an arc, rises, and may rise to such a point that it breaks down to the third cylinder, and the third to the fourth, and so on till the arc has passed entirely across the arrester; then the line current starts flowing across and the distribution of potential is changed, following now a straight line as shown. The potential difference between all cylinders is then the same, and becomes much less than in the case before a breakdown. It is well known that to maintain an arc of alternating current across a gap, the voltage must be at least high enough to re-break down the dielectric each time after the arc goes out at the end of a half-cycle. The dielectric is greatly weakened by the heat produced by the passage of the arc, therefore the voltage to maintain the arc need not be as high as that which originally broke across. The weakening of the dielectric depends on the heat of the arc, and as this depends in turn upon the boiling temperature of the metal of the arc cathode, certain metals when used as electrodes require a higher voltage than others to maintain an alternating-current arc. The connection between the boiling point of the electrode metal and temperature of the arc is as follows: the current is carried across the gap by a stream of metal vapor coming from the cathode. If the metal vapor forms at a low temperature, the temperature of the arc will be low. Unfortunately, the low boiling temperature metals do not hold their form well under the electric arc. It is, therefore, necessary to use alloys rich in these metals. The metals of higher boiling point can not vaporize while those of lower boiling point are present, and so hold the cylinders in form without effecting the temperature of the arc. In the actual lightning arrester, much depends upon the choice of this alloy for the cylinders.

The arresters are, of course, designed so that the voltage gradient shown by the straight line in Fig. 23 is not steep enough to give a voltage across the gaps high enough to maintain an alternating-current arc. An arc following a discharge across the arrester would therefore go out at the end of the half-cycle in which it occurred.

In connection with the physical phenomena which takes place when the dielectric breaks down between cylinders, a note on the characteristics of air as a conductor of electricity is of interest.

Gases in general are such poor conductors of electricity that for long there was discussion pro and con regarding their possession of this property. A very small conductivity, however, exists under normal conditions, and this may be much increased in a number of ways, so that gases under certain conditions are good conductors of electricity. The gases conduct electricity when the temperature is raised above a certain point; when the gas is drawn from contact with incandescent metals or carbon, or is drawn from the vicinity of flames; when an electric charge has passed through the gas, or when röntgen, lenard, or cathode rays have passed through the gas; also when rays from radioactive substances or from uranium or thorium have passed through it; when gas has been exposed to rays from electric sparks; when the cathode is illuminated by ultra-violet light; also when air has passed over phosphorus or bubbled through water. Thus it is seen there are many means of imparting electric conductivity to gases, and not a few of these are concerned in the breakdown of the multigap arrester.

When gas has become ionized by an electric discharge or otherwise, it retains its conductivity for a period which may vary from five to eight minutes, more or less, a fact which has an important bearing on discharges which follow the first breakdown, and also a fact to be taken into consideration in the use of fuses and circuit-breakers.

The partial breakdown of a lightning arrester under normal conditions, when the static spark is playing across the first few gaps, generates rays which assist the breakdown of the gaps exposed to them; and as the breakdown of the arrester is a process of successive steps, the cumulative influence of this action may be considerable. The first discharge which passes across the dielectric or air is a true conduction of electricity by the gas. The succeeding strokes, however, are more or less in the nature of a minute arc stream, as shown by the spectroscope.

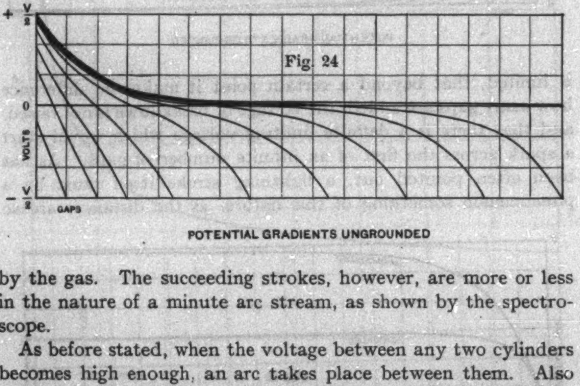

Fig. 24

POTENTIAL GRADIENTS UNGROUNDED

As before stated, when the voltage between any two cylinders becomes high enough, an arc takes place between them. Also voltage is highest between the cylinders nearest the line. Fig. 24 represents a series of potential gradient curves, with number of gaps and voltage just sufficient to start the discharge across the first gap. These curves are for the ungrounded case and follow the approximate equation:

$$V_x = \frac{V}{2} (K^{-x} - K^{x-z})$$

where V_x is the voltage at any point x, *V* is the voltage across any arrester,

g the gaps of the arrester, and

K a constant depending on the ratio between the capacities of cylinder to cylinder, and cylinder to ground. In all these the potential gradient between the end cylinders is seen to be the same and is supposed to be steep enough to break down the dielectric. It is seen that the number of useful gaps is limited, that beyond a certain point it makes no difference how many gaps are added, the voltage of breakdown is not raised, and that there is a definite limiting voltage which would start a spark across the first of an infinite number of gaps. As has been often pointed out, a lightning stroke itself must be a phenomenon something of this nature, as the distances are so great that we cannot conceive of voltage high enough simultaneously to rupture the entire dielectric. The lightning must either break from drop to drop or from dust particle to dust particle, working its way across to its destination.

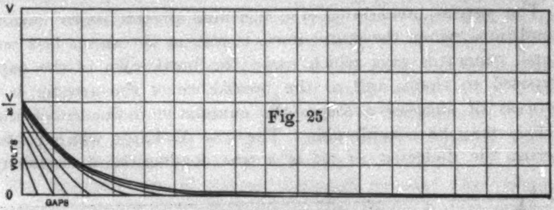

Fig. 25

POTENTIAL GRADIENTS GROUNDED

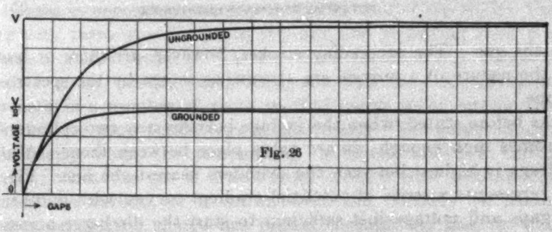

Fig. 26

Fig. 25 shows the condition with one line grounded. In this case the potential gradient between the first and second cylinders is the same as before. It is seen that both the number of useful gaps and the limiting voltage are half what they were before, for where the number of cylinders is such that the curve of distribution of potential becomes tangent to the axis of zero potential, any increase in the number of cylinders does not increase the voltage at which they break down, and this is just half the limiting curve for the ungrounded condition. In the design of the practical lightning arrester, however, we do not work so high on the curves as is here shown, and the curves themselves are altered by the use of resistance. It is to be noted that for a low number of gaps there is little difference between the grounded and ungrounded curves.

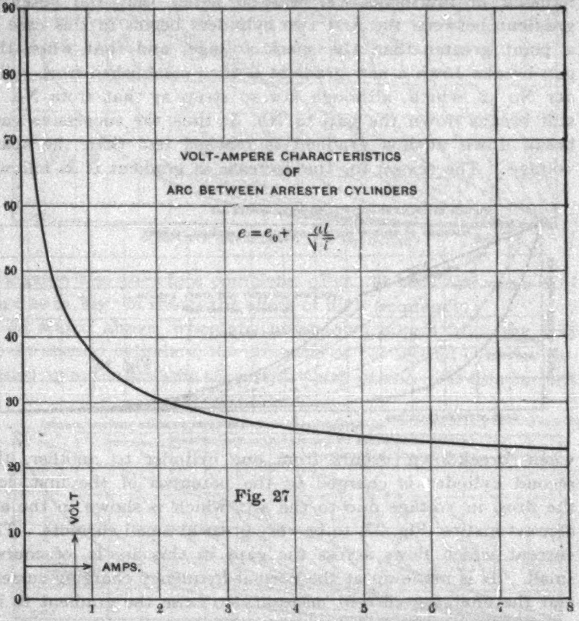

Fig. 27

Fig. 26 shows curves of voltage and number of gaps founded on the curves of Figs. 24 and 25. These curves are of the same shape as have actually been found by test.

Fig. 27 shows the volt-ampere characteristic of the arcs between cylinders, and indicates that the voltage between cylinders is equal to the counter electromotive force of the arc plus a factor which is approximately inversely proportional to the square of the current.

Fig. 28 shows the distribution of potential over the arrester with one line grounded, where breakdown occurs over a number of gaps without a complete discharge. This is one of the phenomena of multigaps. It will be noted that the potential gradient between the first two cylinders begins in this case at a point greater than the spark voltage, and that when this gap breaks down a new gradient is then established from cylinder No. 2, which, although not so steep as that from No. 1, still breaks down the gap to No. 3; thus the successive gaps break down until a gradient is reached less than the spark voltage. The reason for the decrease in gradient is as follows: when breakdown occurs from one cylinder to another, the second cylinder is charged to the potential of the first, less the drop in voltage due to the arc, which is shown in the arc characteristics, Fig. 27, to be very great at small currents. The current which flows across the gaps in this arc is, of course, small. It is made up at the normal frequency charging current and the charging current necessary to raise the gradient to its new position. On low frequency this last is most important. Due to the drop in voltage as the successive cylinders break down, the current through the arcing gaps also decreases, the gradient of drop in voltage following a curve. If the potential gradient as the arrester breaks down from one cylinder to another does not reach a value less than that of the spark voltage, the breakdown of the arrester is complete and discharge passes entirely across the apparatus. This means that either the voltage was higher at the start than in Fig. 28, or that the drop

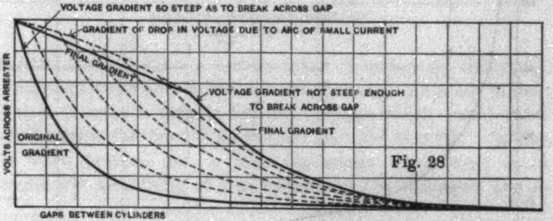

Fig. 28

in voltage between the gaps was less. This is shown clearly in Figs. 29 and 30, which also indicate in the most interesting manner the difference due to the effect of frequency, which is a very important factor with the multigap lightning arrester.

In Fig. 29 the voltage was higher than in Fig. 28 and the discharge was therefore complete. Fig. 30 with the same voltage as in Fig. 28 shows the effect of high frequency.

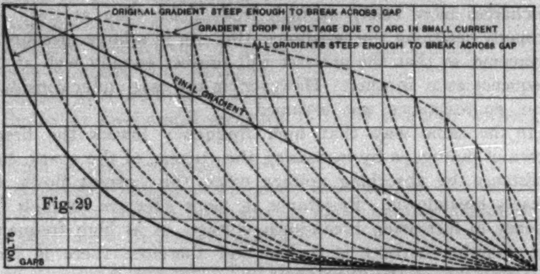

Fig. 29

COMPLETE BREAKDOWN LOW FREQUENCY

As stated above, when the breakdown occurs from the first to the second cylinders, the potential of the second cylinder depends upon the amount of current which passes. As this current is that due to the capacities, which have been considered, it will be greater at high frequencies and the fall of potential between the first and second cylinders will therefore be less. As the arrester gaps break down successively, the fall of potential from one cylinder to another is less, and therefore such an arrester will discharge at a lower voltage for a higher frequency

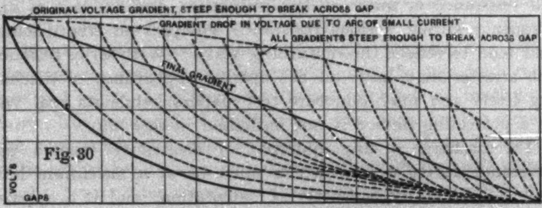

Fig. 30

COMPLETE BREAKDOWN HIGH FREQUENCY

than for a low. At high frequency, due to the inductance of the cylinders themselves, the normal gradient is steepened; this also assists breakdown. In such cases (Figs. 29 and 30) where the arrester discharges completely, no point is reached where the potential gradient is less than that of the spark voltage.

As is well known, the multigap arrester without resistance discharges more easily at high frequencies than at low. By properly designing the resistance, this can in a large measure be overcome, so that the arrester will protect equally well at one frequency as at another. However, in the case under consideration, no resistance was assumed.

In the same way that high frequency lowers the breakdown of multigaps by increasing the current of the spark, high resistance, by absorbing voltage when this current flows, decreases breakdown. Resistance is more effective at high frequency in increasing breakdown voltage, as at high frequency the charging current is higher and therefore there is more voltage drop in the resistance.

Resistance. Resistance is one of the important factors of lightning-arrester construction. Its usual functions are, in general 1, to limit the current, 2, by shunting part of the arrester to give fewer gaps for low frequency to break across.

Series resistance limits the current under all conditions, but, although in this way protecting the arrester, it is dangerous in case of a surge. It has still another and perhaps worse effect. All resistance is more or less inductive, and in case of high-frequency stroke, serious resistance will prevent free discharge and tend to reflect the disturbing wave. With series resistance the arrester may have all the optical appearance of discharging freely and may puncture test papers, while its real value as a protecting device is not indicated in any way.

The discharge of any quantity of electricity from a good resistance during a time which must be at a maximum but a half-cycle is easily a matter of calculation, and it is apparent that, other things being equal, the protection afforded by an arrester is inversely as the amount of series resistance.

As will be described below, an arrester has been developed in which no series resistance has been used, but in which resistance nevertheless limits the current of discharge except in extreme cases of surge. Resistance also makes the arrester break down at uniform voltage at all frequencies and assists to discharge surges.

The desirable characteristics of resistance are as follows, it being impossible to obtain them all in any one known combination:

1. Sufficient heat-absorbing capacity.
2. Surface of such character that arc will not flash over.
3. Must be easily replaceable.
4. Non-absorptive as regards moisture.
5. Uniform conductivity over section.
6. Non-inductive and straight.
7. Should have no coherer action.
8. Sufficient mechanical strength to stand red heat without failing.
9. High specific resistance.
10. Resistance should not change with use.
11. Must not become incandescent under service conditions.
12. Must allow of good contacts.

Ideal Lightning Arrester. The ideal lightning arrester should prevent any rise of voltage dangerous to insulation. It should offer a free path of discharge from line to ground and from line to line, and should preform its functions without disturbing the operation of the system. It should put out the arc at the end of the half-cycle in which it starts, and should have no discrimination in its protective power as regards the frequency of the disturbance. That is, it should discharge at a certain voltage for any frequency. An arrangement of gaps and resistance as shown in Fig. 31 meets this last condition in this way; gaps alone break down more easily at high frequencies, but high frequencies will not readily break down through both resistance and gaps. Low frequency is not impeded as much by resistance, but can break through only a few gaps for the same voltage compared with high frequency. For a given voltage, then, the higher frequencies would break through the path with gaps only; frequencies somewhat lower, through the path with moderate resistance; and low frequency and accumulated static through the path with the high resistance. An arrester of this type, however, possesses the disadvantage that after a voltage of low frequency breaks across the gaps in series with the high resistance, the current which can follow cannot relieve the line. This can be overcome by an arrangement such as shown in Fig. 32. In this case the same paths of breakdown for the different frequencies are retained, but now if low-frequency breaks down the gaps in series with the high resistance, the entire voltage less that consumed in the arcing gaps is concentrated across the next highest division of gaps. These, if correctly designed, will at once break down, passing the strain still farther up the arrester, and so on, the arrester breaking down in sections until it is either completely broken down or the line voltage has been lowered by the current flowing through the resistance. This idea has been worked out in the design of a new line of arresters described below.

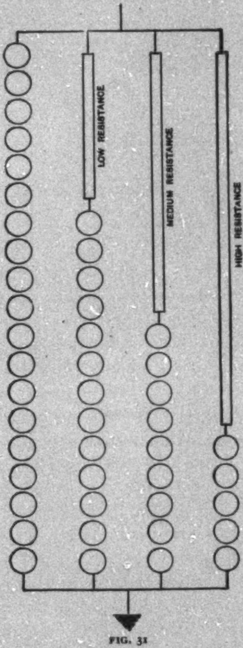

FIG. 31

The Graded Resistance Lightning Arrester

During the last year a very large amount of experimental work has been done to develop the multigap arrester, and it is felt that the results obtained will be, so far as can now be seen the maximum development of this type of apparatus.

The multigap lightning arrester has had the property of responding more readily to high frequencies than to low. In the new designs, however, by the use of resistance, as just described, this has been, so that a low frequency now discharges with the same facility as high frequency, and the discrimination with regard to that condition is largely removed.

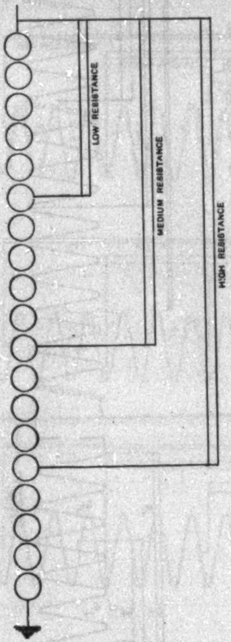

FIG. 32

The arrangement for these arresters for 35,000 volts is shown in Fig. 33 for the delta and ungrounded star transformer connections, and Fig. 34 for grounded star systems. In each case we have three legs made up of *V* form multigap units, Fig.

35. Each leg is connected to one of the lines through a spark gap shunted by a fuse. Connected in just below the fuse we have a novel device, in that we have the three resistances in parallel, tapping in to different parts of the leg as shown. These three line legs are joined at their lower ends by a common or

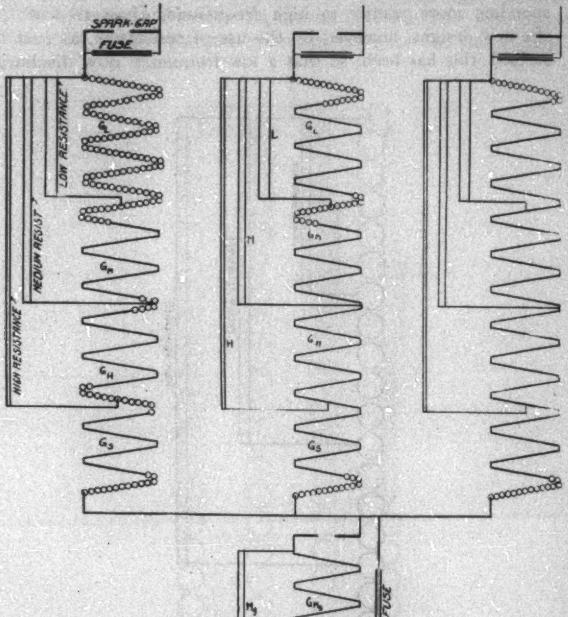
SPARK-GAP
FUSE
LOW RESISTANCE
MEDIUM RESIST
HIGH RESISTANCE
G_L
G_M
G_H
G_S
L
M
H
G_L
G_M
G_H
G_S
M_3
G_{M_3}
L_3
G_{L_3}
FUSE

Fig. 33.

multiplex connection, from which, for ungrounded systems, a fourth leg connects to the ground. In the arrester for grounded star systems no fourth leg is added, the multiplex connection being connected to ground.

Fuses. The use of a fuse in shunt with the spark-gap is for the condition of continuous high voltage on the lines from any cause, an arcing ground or otherwise. The fuse will then blow

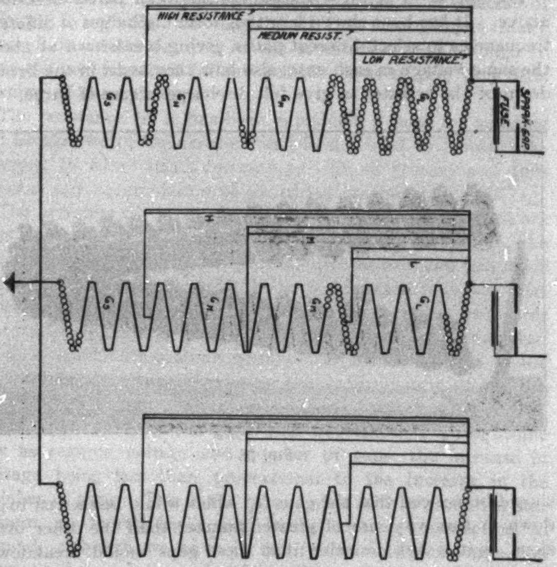

FIG. 34.

and it will throw the gap in series with the arrester and thus bring about an automatic adjustment of the gaps. This allows the arrester to be adjusted to discharge at but a small percentage above the line voltage, and thus to afford real protection. The introduction of the extra gap does not destroy the arrester as a protective device; it merely adds a factor of safety against the destruction of the arrester. If this fused gap were omitted, its equivalent would have to be introduced as additional multigaps. This fuse is so proportioned that it will not blow at an ordinary discharge. The small complication of the addition of this device is much more than offset by the close adjustment possible in the arrester, thus allowing the best protection to be had.

Resistances. The three resistances, designated respectively *L*, *M*, and *H* for low, medium, and high, represent a distinct advance in the art of lightning-arrester design.

The operation of these resistances has been partly described above. It has been shown how they force discharges of different frequencies to select different paths, giving breakdown at about the same voltage in each case; also how they assist in the breakdown of the arrester to give full discharge in case of surge. It should be noticed that the gaps G_1, which would be the last to go down in this way, are of greater number than the other divisions, as it is not desirable that these gaps should breakdown except under extreme conditions. The low resistance, *L*, should be able to discharge the line sufficiently to relieve the voltage. It must be clearly understood that the use of the word "breakdown" means the discharge, not the failure of the arrester. It has been found that when gaps are shunted by resistance and the resistance is low enough, dynamic current will not follow a high frequency across those gaps, but will shunt at once to the resistance. Such a relation exists between the gaps G_1 and the resistance *L*. This being the case, it is seen that the resistance *L* is practically a series resistance so far as the

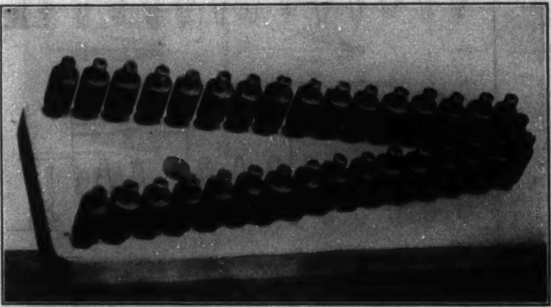

Fig. 35.

safety of the arrester is concerned, but that it introduces neither of the objectionable features mentioned above. High frequency discharges do not have to pass through it, and the shunted gaps can arc over in case of necessity.

Another point to be brought out is that when gaps in series with resistance, such as L and G_m, are shunted by a second resistance such as M, a certain relation will bring about a condition such that a discharge of high frequency down the arrester will be followed by dynamic shunted through M instead of through L and G_m. M may be in this arrangement many times L in resistance, and in the arresters is high enough to limit the current which follows a stroke so as to give very little burning of the cylinders.

The resistance H, as has been explained, is used for assisting the breakdown of the arrester, and is also used as a static discharger, to allow small currents to leak to ground and thus prevent any accumulation of electricity on the line.

The arresters of this type are so designed that, should the arc pass across all of the gaps following the static discharge, the number of gaps is sufficient to extinguish the arc, and this holds with each resistance and with the gaps connected with it. That is, any current which might start across any of the resistances and the corresponding gaps would immediately be extinguished by that combination alone without the shunting effect of the other resistances, thus rendering the extinguishing of the arc doubly secure.

The breakdown of the gaps does not follow a straight-line law as regards voltage and number of gaps, the increase in voltage being less than proportional to the increase in the number of gaps. This is the reason why, with a grounded star system, no fourth leg is used in the arrester connection to ground, although we have in reality the multiplex connection between line and line. In this arrester the same margin for breakdown exists between line and line as between line and ground, but twice the number of gaps in series do not require twice the voltage to break over them, but with these proportions, approximately the voltage multiplied by $\sqrt{3}$.

With regard to the grounded leg, the fuse is so connected with the L_g resistance that but few gaps are in series, and we have a sensitive condition where the arrester will discharge easily at low as well as high frequencies. When, however, the fuse in the grounded leg blows, due to a ground on the line, we still have an arrester which will protect the line with one phase grounded, without suffering any injury to itself.

Lightning arresters of the form shown in Figs. 33 and 34 have been designed for the following voltages: 6,600, 10,000, 12,500, 15,000, 20,000, 25,000, 30,000, 35,000, 40,000, 45,000, 50,000, and 60,000 volts. Anything between these voltages is, of course, taken care of by the arrester on one side or the other, as is thought best. For lower voltages, down to 300 volts, the arresters are of slightly different design, having only two resistance rods. The 2300-volt arrester is shown in Fig. 36. For voltages below 300 volts no resistance is necessary, as the voltage is so low that the arc can never hold. These arresters, therefore, consist simply of single spark-gaps to be connected directly across the line.

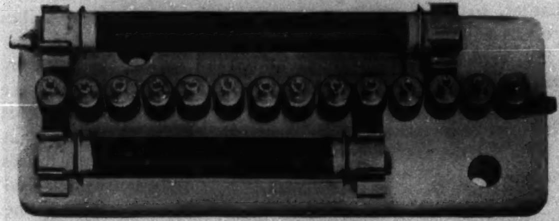

Fig. 36.

The 2300-volt arrester, Fig. 36, being intended for pole as well as station use, is necessarily simpler in design than the high-voltage arresters. It consists of 14 cylinders, 9 of which are shunted by a low resistance and 11 by a high resistance. As in the case of the higher voltage arresters, the grading of resistance makes this arrester discriminate between frequencies, giving each a path to break down that requires a voltage not too high or too low. Accumulated static passes off across the high resistance and two gaps in series. High-frequency discharges pass across the entire arrester; moderate high frequencies across the low resistance and four gaps. The low resistance is, as in the other arresters, proportioned with the number of shunted gaps so that the high-frequency discharge across these gaps is never followed by the dynamic current, the dynamic shunting at once to the low resistance. A photograph of this arrester discharging is shown in Fig. 37. Note that a discharge takes place over all the gaps, but that the arcs between the gaps shunted by the low resistances are very small compared with the bright arcs between the last four gaps. The static discharge is passing through all the gaps, while the half wave of dynamic current following the static is shunted part of the way by the resistance.

Fig. 38 shows an oscillogram of this phenomenon. It is seen that the only current in the shunted gaps is the current of static discharge. It should be noted that the current shown is not a measure of the true current, as the oscillograph can not respond to currents of such high frequency.

Fig. 39 shows an interesting oscillogram. Here both the total number of gaps and the shunted gaps were reduced to a point considerably below the safe limit. The static discharge was at once followed by a half cycle of short-circuit current across all the gaps, voltage falling almost to zero. The following half-cycle, however, shows that the current left the shunted gaps and flowed through the resistance, extinguishing entirely after the end of this half-cycle. With the small number of gaps used, if it had not been for the resistance the arc would have undoubtedly and the arrester would have been destroyed. This merely held shows the protection offered by a shunt resistance a step below that designed. In a correct design, the dynamic could not have started across the shunted gap in this way, and the total number of gaps is sufficient to extinguish the arc of short circuit,

Fig. 37.

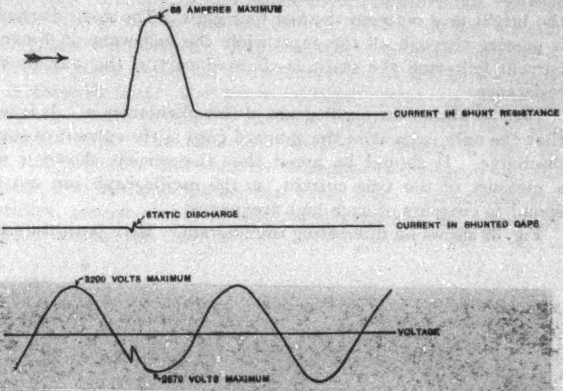
88 AMPERES MAXIMUM
CURRENT IN SHUNT RESISTANCE
STATIC DISCHARGE
CURRENT IN SHUNTED GAPS
3200 VOLTS MAXIMUM
VOLTAGE
2270 VOLTS MAXIMUM

FIG. 38

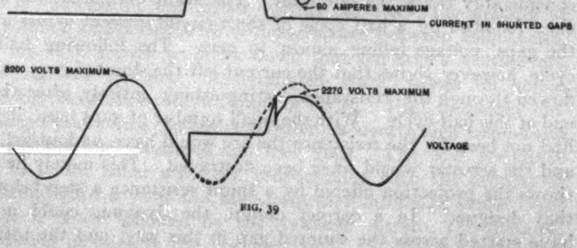
220 AMPERES MAXIMUM
STATIC DISCHARGE
5.4 AMPERES MAXIMUM
CURRENT IN SHUNT RESISTANCE
80 AMPERES MAXIMUM
CURRENT IN SHUNTED GAPS
3200 VOLTS MAXIMUM
2270 VOLTS MAXIMUM
VOLTAGE

FIG. 39

even with no resistance. Returning to the low-frequency breakdown; as before stated, accumulating static merely discharges over the two end gaps. For a rise in generated voltage or a power surge, however, the current which could discharge through the high resistance would have no protecting effect. But with these two gaps broken down and arcing across, the high voltage would be concentrated across the next two gaps. As practically the same voltage broke through the first two, these will at once break down, allowing a discharge through the low resistance which should be able to take care of the system. To sum up, the effect of this use of resistance is as follows: the high resistance discharges static at low voltage and assists breakdown in case of surge. The low resistance allows low breakdown in case of surge, gives correct breakdown to medium high frequencies, reduces the burning of the cylinders and in that way gives the arrester longer life, and prevents any disturbance of the system which might result from a half-wave of short-circuit to ground.

This arrester is designed to operate across 2300 volts. It is used, however, from each line to ground, it giving in that way sufficient protection and being always able to handle a discharge when one line is grounded. It is built to be used single-pole, but by placing two or three in the same box, becomes double-pole or triple-pole.

On grounded systems this arrester can be used up to 4,000 volts between lines. On ungrounded systems by using two arresters line to line and one from the middle to the ground, this arrester can be used up to 4,000 volts.

The 1000-volt arrester is nearly the same in design but has only one series gap below the high-resistance rod.

A paper presented at the 217th Meeting of the American Institute of Electrical Engineers, New York, March 29, 1907.

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NEW PRINCIPLES IN THE DESIGN OF LIGHTNING ARRESTERS*

BY E. E. F. CREIGHTON

The installation of lightning arresters is of the nature of an insurance. A certain percentage of the cost of the apparatus can reasonably be invested as a safeguard in protecting the apparatus. Furthermore, a percentage of the income can also be invested in protective apparatus as an insurance against interruption of service. The value of uninterrupted service depends upon the nature of the use of the current and will consequently vary in different plants. Plants which make contracts involving penalties for interrupted service naturally put a higher premium on good service. Protecting the insulation of the apparatus has been an easier matter than protecting the continuity of service. It has sometimes happened that the service has been interrupted by the action of the protective apparatus itself. This is especially true in the case of a grounded phase on an insulated delta or Y system.

It is the opinion of the writer that we have in view complete protection at the terminals of the lightning arrester apparatus against any high potential surge above 150% of the normal voltage of the system, regardless of the natural frequency of the surges and the duration of their application and also regardless of the cause of the surges. Direct strokes of lightning on a transmission line must of course be taken care of where they strike. Arresters at some distance away in the station can be expected to take care of only that part of the charge which reaches the station. How thoroughly a grounded overhead wire will pro-

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* This is the first of two papers on this subject.

protect the line from direct strokes has not been fully determined, or otherwise put, how many and what conditions of overhead grounded wires are necessary to protect the line against direct strokes of lightning is not definitely known.

Arresters can be built to take care of high-frequency surges, low-frequency surges, grounded-phase surges during an hour or so, and standing waves. This leaves the causes of interruption of the electrical circuit limited to short-circuits. These short-circuits may be limited to accidental conditions, such as a wire thrown across the transmission line, overheated apparatus, etc.

ON THE DESIGN OF MULTIGAP ARRESTER.

The novel features of a new multigap arrester consist first, of the discovery of a true nonarcing condition of shunted gaps; secondly, a combination in a cumulative manner of several shunt resistances, and thirdly, the design of ohmic resistance by the volume method rather than by the radiating surface.

First; *Absolute Nonarcing Condition.* The term "non-arcing" has long been misused in the sense of arcing during only the brief time of a half cycle or only a few cycles of the generator wave. This action is more correctly described by the term rectifying. By the term "non-arcing" in the present application it is meant that the condition of sparking exists without the formation of an arc. Transition of a spark, where the conducting medium is the heated air, to an arc where the passage of electricity is accomplished by means of convection in the arc stream of zinc vapor, involves the expenditure not only of energy but also of power.

The discharge of several hundred amperes for a brief period has been produced across a gap without bringing the difference of potential across the gap down to the normal value of 40 volts, corresponding to a current of one ampere. The power in this case was large as compared to the energy. In this connection brief periods approximating 1/100,000 second are considered. It seems to require an expenditure of power for a much longer time to bring the arc voltage down to even 100 volts. As the heating continues the voltage decreases. This effect is shown in Fig. 1. The voltage of any increasing value of current is higher than the voltage of the corresponding decreasing value, (see the two lower curves).

The difficulty in the initial transition from the condition of spark to the condition of arc is shown by another test on the same brass cylinders. Forty-five volts from a storage battery were applied to a 1/32-in. gap and a discharge of a Tesla coil was passed continuously across the gap for several minutes without causing an arc to form. In other words the battery gave out no energy. This is a case of a considerable energy at low power failing to cause an arc. It is seen from Fig. 1, however, if the impressed voltage of the battery is higher the arc will form and the arc voltage will drop far below 45 volts.

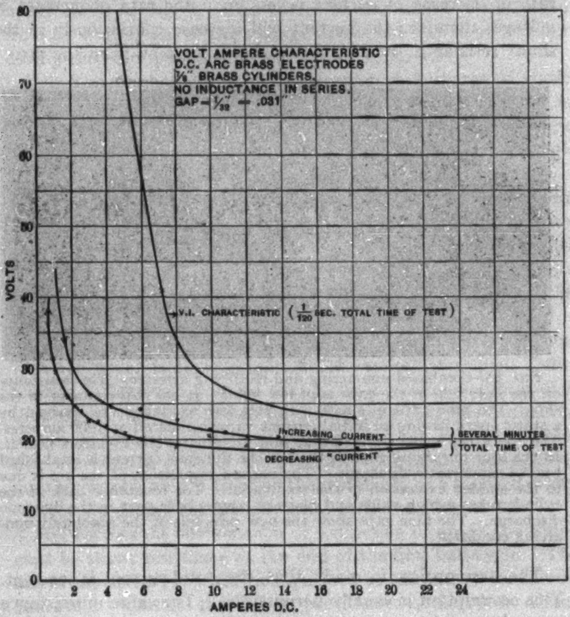


FIG. 1.

It is possible to discharge induced static electricity over multigaps directly to ground without the intervention of series resistance and still prevent the dynamic current of the generator from following the static spark, with the resultant short circuit. This condition requires an adjustment of the resistance in parallel with the gaps such that the current will be transferred to the resistance before the heat expended in the gaps is sufficient to bring the arc voltage to a low value. The problem is that of the instability of an arc (which is well known) under the unknown condition of volt-ampere characteristic of an initially established arc. The condition of instability of an arc and resistance in parallel will now be considered using the volt-ampere characteristic (middle curve) of Fig. 1. This curve shows that the arc is extinguished by any resistance in parallel which reduces the current of the arc to about four amperes. Below four ampere the rate of decrease of current is less than the rate of increase of voltage, therefore the current will increase continuously in the shunt resistance, stealing away all the current from the arc.

FIG. 2.—Combined non-arcing and rectifying arrester. The resistance on the near side of the gaps is of low value. It has cap contacts in the slips. The nine gaps in shunt with this low resistance are bridged by a static spark having an initial current value estimated at 1000 amperes. The spark has a clean cut outline and illuminates the cylinders near it. In the four remaining gaps to the left the dynamic current is established by the same static discharge. The blurred impression of the arc is due to the sudden expansion of the zinc vapor. The resistance back of the cylinders has a high value and plays no appreciable part in the dynamic discharge. The nine gaps show the new principle of the absolutely non-arcing condition.

The assumption is made that the total current is constant. This assumption is usually permissible. The value of resistance in parallel which causes the arc to become unstable depends on the value of total current; the higher the total current the less must be this value of resistance. For example, in the volt-ampere curve considered, if the total current is 10 amperes, it requires four ohms in parallel to make the arc go out. If the total current is 22 amperes, the shunt resistance must be reduced to 1.3 ohms to extinguish the arc. If the total current is 500 amperes the resistance is parallel must be reduced to 0.05 ohms.

This last mentioned value is too low to be of practical importance. Lightning discharges may easily reach 500 amperes, but it must be recalled that the volt-ampere-characteristic curve of the initial discharge lies far above the two curves given in Fig. 1, consequently a very useful value of a few ohms per gap will extinguish this spark before the dynamic arc can be established. The more favorable condition for the shunting of the gaps when the arc is just being started is shown in the upper curve of Fig. 1. The values of this curve were taken from an oscillogram of the voltage across one gap of an arrester during the brief period of a half cycle (1/120 sec).

Fig. 2 is a photograph of the combined discharge of static electricity and dynamic current. In the shunt gaps there is nothing but the spark, whereas in the series gaps both the spark and arc bridge the gaps. The arc is shown in the photograph by its greater size and explosive stream of zinc vapor.

Fig. 3 is an oscillogram of the currents of the two shunt circuits and the potential across the arrester when the factor of safety is diminshed by having only six gaps in the parallel path. The potential across the arrester drops from 3,200 volts maximum to 2670 volts maximum due to the line drop and the regulation of the generator.

In order to avoid confusing the above described phenomenon with the usual familiar conditions of shunted multigap, a distinction is herewith pointed out. The unstable condition of a shunted arc has been known for a long time; but this instability has to do principally with alternating current, whereas in this case only half a cycle of the generator potential is considered; in other words, we are treating the instability of a shunted direct current arc during the initially brief period of formation.

Fig. 4 shows the phenomenon of extinction of arc in the shunt gaps by shunt resistance at the end of the first half-cycle. The arc in the series gaps was extinguished at the end of the second half-cycle. This is the effect previously obtained in shunt resistances where heavy currents were used. In this test the ohms per shunted gap were too great to suppress the initial arc.

There is still much research to be done to determine the exact nature of the phenomenon at the instant of establishing and extinguishing an arc. Most of the results are of academic interest only. Here are some queries. In the extinction of the arc in the series gap at the end of the half cycle in which the discharge takes place, how much effect is due to rectification of the zinc vapor and how much to the cooling of the arc during the brief period of zero current? The answer is not simple, we know. For small currents, the effect is almost entirely due to cooling; for large currents, rectification by the zinc vapor is more prominent. The distinction is liable to be obscured by the two auxiliary accompanying conditions—first, the ionization of the air around the zinc arc and, second, by the splashing across the gap of the superfluous molten metal in the crater of the arc. Some years ago Mr. Thomas stated that it was necessary to limit the current in a multigap arrester in order to get

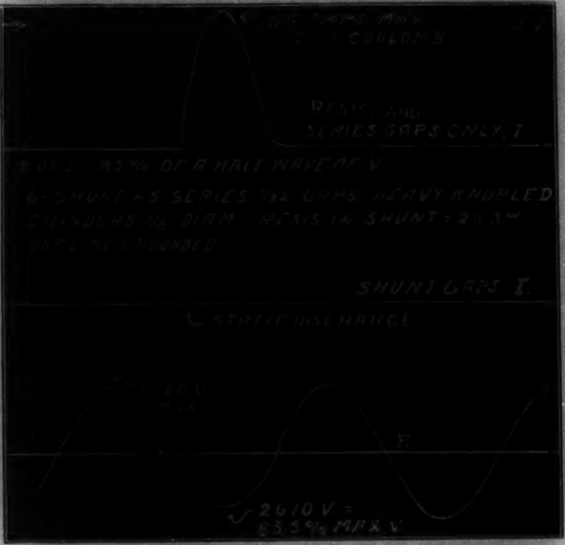


Fig. 3.—Oscillogram 57. Dynamic discharge when gaps are shunted to the absolute non-arcing condition. The upper curve is the current wave through the series gaps and low resistance. The middle curve shows the static discharge (and what little dynamic follows) in the shunted gaps. The lower curve shows the potential across the arrester inside the lightning arrester choke coils. The sudden drop in the voltage wave when the spark takes place is due to the regulation of the circuit. There is a 16% drop. The actual maximum voltage across the arrester is 2670 max. This is divided thus: 2590 volts across the resistance and 80 volts across the series gaps.

successful operation and also that the extinction of the arc was accomplished with greater difficulty if the circuit was inductive. The explanation of these facts have a practical bearing on the matter given further on in this paper.

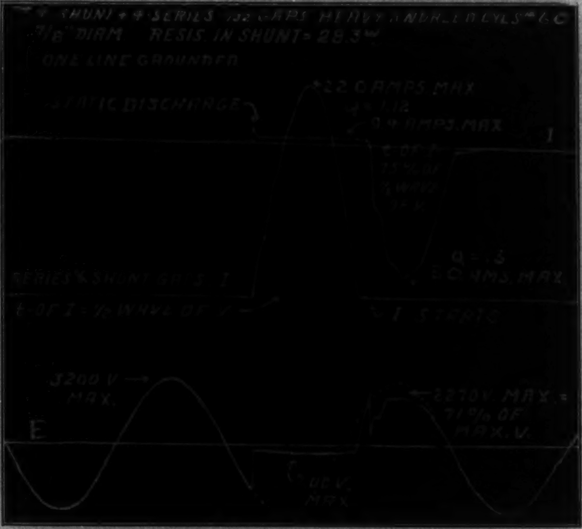


FIG. 4.—Oscillogram 60. Failure of shunt resistance. Former "non-arcing" condition. There are only 4 gaps in shunt with 28 ohms. The upper curve is the current through the resistance. Note the point marked "static discharge," the current in the resistance starts at a value greater than can be maintained. The current in the resistance is equal to the voltage across the shunt gaps divided by the resistance. This peak value bears out the statement that both energy and time are necessary to form a stable arc of normally low voltage value. The middle curve shows nearly short-circuit condition of the circuit. Note that this current lags the potential while the current in the wave above with resistance in series is in phase. The lower curve, the potential wave shows the condiion of sensibly short-circuit in the first half-cycle and the recovery in the second half-cycle. Note in the second half-cycle that the voltage jumps to about 2500 volts before the current is reversed in the series gaps.

Current Effect.—The extinction of an established arc in a multigap arrester cannot take place until the potential reduces to zero at the end of the half cycle in which the discharge takes place. Incidentally it may be remarked that if the arrester functions properly the arc should not extend over the second half cycle. (Assuming no high potential surge reestablishes the arc). If the rectifying power is not sufficient to extinguish the arc at the end of the first half cycle, it surely will be unable to do so at any instant later on account of the heated metal in the arc crater. (See Fig. 9). Consequently such an arc can be extinguished only by the flashing out of the multiarcs in one long arc in front of the arrester unit, the opening of the circuit elsewhere by a fuse or switch, or by the decrease in the generator electromotive force. This decrease in potential will be due to the reaction of the armature current on the field winding. Assume then that the arrester functions properly, and furthermore that the spark takes place on the rising point of the electromotive force wave, this gives the greatest possible discharge of dynamic electricity. The energy loss in each arc will be equal to 16 volts multiplied by the current. In other words, as the current increases there is a concentration of energy at the arc crater which melts more zinc than is necessary to supply the arc vapor. This molten zinc is splashed across the gaps and destroys the rectifying qualities of its vapor.

In consequence of the necessity of limiting the dynamic urrent, some designers have chosen between two evils and introduced series resistance into the arrester circuit. Other designers choose the evil of a possible short circuit. One improvement in design for this year is the use of a shunt resistance so proportioned as to prevent the dynamic current flowing in its parallel gaps, yet allowing a high-potential, high-frequency discharge to pass freely across the shunt gaps to ground, if the resistance offers an objectionable impedance. There is resistance for the dynamic but no resistance for heavy static discharges.

Inductive Circuit Effect.—Oscillograms show that if the arrester circuit is inductive the arc is not extinguished until the potential has passed through zero and is well along in the second half-cycle. Since the arc voltage is only 16 volts per gap for heavy currents the condition is nearly equivalent to a short circuit. When the current dies out the voltage across the gaps suddenly jumps to the value generated. (See Fig. 5). The arc has no time to cool and presumably the ionized air around the arc starts the current in the opposite direction. This condition is to be compared later to the condition of arc extinction in the liquid electrode arrester, where the current reduces to zero before the potential.

2. Cumulative shunt resistance. Referring to the diagrammatic condition of Fig. 6, gaps No. 8, 9, and 10 are protected from dynamic current by the relation of the shunt resistance (r). The resistance (r) is small and requires, seven series gaps, Nos. 1, 2, 3, 4, 5, 6, and 7 to extinguish the dynamic arc. Under certain low-frequency conditions of discharge this number of series gaps is objectionably great. Consequently this number is cut down to, say, three gaps, No. 1, 2, and 3, and in order to extinguish the dynamic arc at the end of the first half-cycle the current must be less than that through the small

Fig. 5.—Oscillogram 253. Showing current lag, sudden recovery of potential, and displacement of another phase of the system. In the lower curve note the potential recovery when the current is extinguished. The dotted curve shows the original form of the wave. The middle curve shows 434 amperes short-circuit current. There were 3 miles of line wire to the generating station. The upper curve shows the phase displacement in phase 1 due to the reaction of the armature current in phase 2. It is noteworthy that the voltage wave of phase 1 did not have a peak value above normal maximum of 3200 volts during this interval.

resistance (*r*); the relation of the larger resistance (*R*) to the gaps numbered 4 to 10 inclusive is not such as to obtain the arcless condition of the gaps. The arcless condition of the gaps 4, 5, 6, and 7 is obtained through the presence of the small resistance (*r*) in shunt with the large resistance (*R*). So far as the large resistance R is concerned, gaps 8, 9, and 10 cannot be considered in the shunted circuit. In this cumulative manner of installing the resistance, the series gaps may be reduced to as near the spark potential of the normal circuit voltage as desired. Each time the series gaps are reduced, the resistance must be increased to such a value as to maintain the arc extinguishing effect.

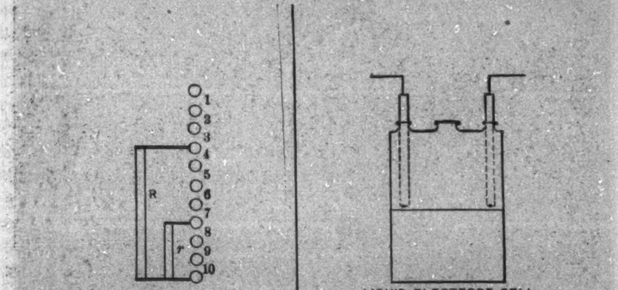
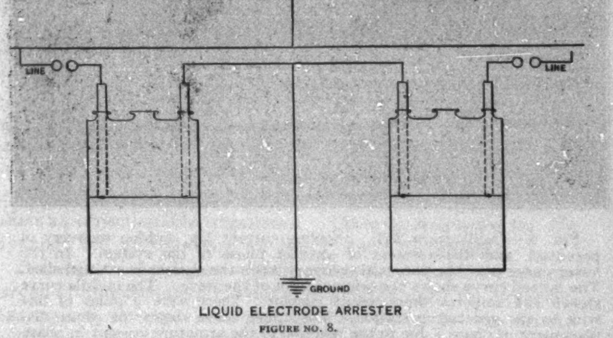


FIGURE NO. 6.

LIQUID ELECTRODE CELL
FIGURE NO. 7.



LIQUID ELECTRODE ARRESTER
FIGURE NO. 8.

FIGS. 6, 7, AND 8.

Design of Lightning Arrester Resistance. Except in the case of recurring high potential surges the multigap arrester should extinguish the dynamic arc within the time of a cycle of the generator wave. This period of time is so brief that radiation of heat need not be considered in the design of the resistance. The basis of design is the utilization of the specific heat or the heat capacity of the resistor. In the lower resistances of the lightning arrester it would be impracticably expensive to design the resistance to radiate the energy that would be lost therein if the current were applied even for several seconds.

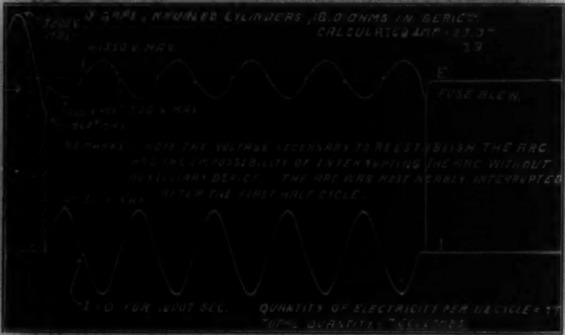


FIG. 9.—Oscillogram 29. Three gaps and 18 ohms on a 2300 V. (effective) circuit. Arrester fails to interrupt the current of 137 amp. maximum. If the arc is not extinguished at the end of the first half-cycle, the rectifying effect is lost. The spark takes place at 1860 volts increasing potential. The voltage then drops due to line resistance, etc., and reaches 880 volts max. instead of 3200. At the end of the first half-cycle the potential rises to 1350 before the current is reversed. At the end of the second half-cycle it requires only 320 volts to reverse the current. At the end of the first half-cycle on the current wave, the current remains zero for a brief period. This effect does not reoccur at the end of any subsequent half-cycle. If the current had been less three gaps would have extinguished the arc at the end of the first half-cycle.

E^2 over R multiplied by the time of a half cycle gives the energy to be absorbed. This value of energy must equal the product of the specific heat times the weight of material times the temperature times 4.2.

Assuming a safe temperature and factory of safety the weight of the material can thus be determined.

The specific resistance of the material must be chosen so as to give a length of rod great enough at least to prevent the formation of an arc along the surface. In the matter of selection of material for the resistance, notable improvements have been made.

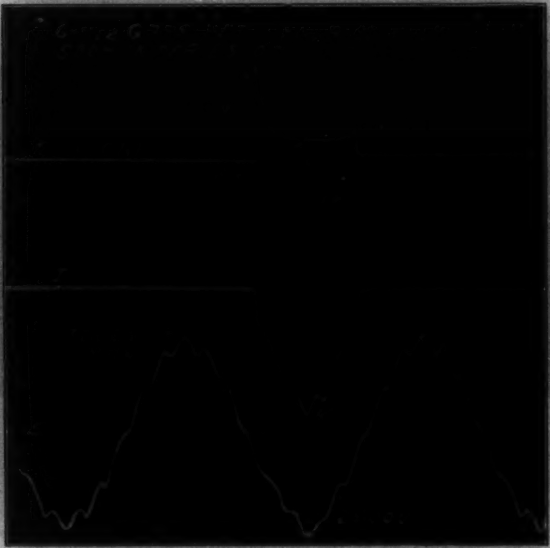


FIG. 10.—Oscillogram 156. Voltage and current of one gap of a multigap arrester. The oscillogram shows an initial voltage of 93 volts. The drop from spark voltage to 93 volts was too rapid to be registered by the oscillograph vibrator. This sudden drop in potential was due to the heavy discharge from Leyden jars at a frequency estimated at 3,000,000 cycles. The decrease in voltage from 93 to 23 volts is very gradual with this value of current density. The upper volt-ampere characteristic curve of Fig. 1 was taken from this oscillogram.

LIQUID ELECTRODE ARRESTER.

The name "liquid electrode" is herewith given to a new form of electrolytic type of arrester, to distinguish it from the other cell types of arresters, such, for example, as the aluminum-cell type which the writer has been working on during several years. The liquid electrode is the distinguishing feature of this electrolytic type, whereas the hydroxide film of aluminum on the aluminum plate is the characteristic feature of the aluminum-cell type. The phenomena which can be produced by the discharge of electric currents through electrolytes are of such a nature as to make valuable the employment of an electrolyte in protective apparatus. The main effect obtained in each

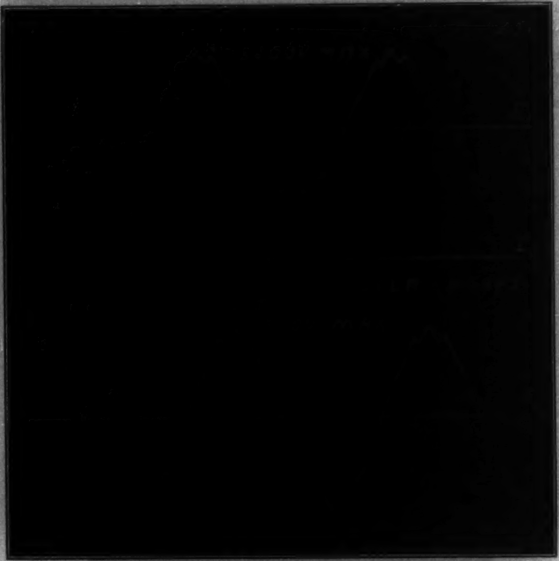


FIG. 11.—Oscillogram 251. Six gaps and no series resistance on a 3-phase circuit of 2300 volts effective. The middle and lower curves are of the same phase. These show a discharge of dynamic current where the spark takes place on the descending part of the potential wave. In spite of the short-circuit of the gaps the dynamic current rises only to 25 amperes. In practice the spark may of course take place at any point of the potential waves. In a poorly designed arrester if by chance the spark should happen when the potential is approaching zero the arrester will extinguish the arc satisfactorily; if, on the other hand, the spark takes place on the rising potential the effect may be that shown in Fig. 9. This oscillogram shows the futility of testing arresters without a synchronous switch to control time of spark discharge.

case may be designated as a *critical limiting voltage*. The employment of a *critical limiting voltage* in lightning arresters permits the design of an arrester which will limit or suppress entirely the dynamic current at normal potentials, without the use of series resistance. Abnormal potentials above the *critical limiting voltage* of the arrester discharge current through the arrester freely without obstruction of either counter electromotive force or appreciable ohmic resistance. The characteristic action of the electrolytic types can be summed up in one sentence: obstructed discharge of electricity at normal potentials of the circuit and free discharge of electricity at abnormal potentials. The electrolytic types give great promise.

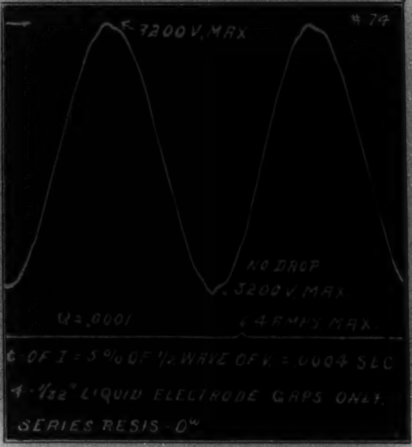


FIG. 12.—Oscillogram 74. Liquid electrode arrester using gaps at the surface of the electrolyte. Two cells in series. The current rises only to 0.4 amperes and there is no disturbance in the potential wave.

The liquid electrode arrester may have any one of several forms all involving the same principal. One form is shown in Fig. 7. Two metallic electrodes extend into a vessel containing an electrolyte of high conductivity. The electrodes may be dipped into the electrolyte or there may be a small gap left between the electrode and the electrolyte If current is passed from one electrode to the other in either direction, the liquid must become negative at one or the other electrode. It requires about 1500 volts to maintain the current through the cell in spite of the fact that the resistance of the cell is extremely low. The current is limited by the so-called counter electromotive force of the arc.

Electrodes not in Contact. The difference in effect produced by the conditions of contact between the electrodes as compared to the air-gap setting is marked. For example, three of these cells were placed in series across a circuit having an impressed voltage of 2300 volts effective. Each electrode was set with a small gap. The equivalent needle-gap was the same as for four $\frac{1}{32}$-in. gaps between standard brass cylinders without series resistance. With this arrangement several hundred static discharges having an initial value estimated at 1000 amperes were passed through the cell, but no

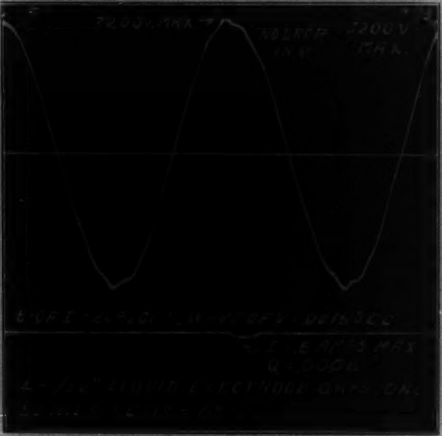


FIG. 13.—Oscillogram 73. Liquid electrode arrester using gaps at the surface of the electrolyte. Although the spark takes place at peak voltage only 0.8 ampere of dynamic current follows. Comparing the current discharge to Fig. 12, the current is twice as great and persists for a longer time. This is due to the fact that the discharge takes place at a higher point on the potential wave. The counter e.m.f. of the cells is approximately equal to the peak voltage (3200 volts) of the circuit. There is no disturbance of the potential wave.

dynamic current followed the discharges. The novel relation of counter electromotive force practically as great as the spark voltage of the cell is obtained. The sum of the counter electromotive forces per cell is greater than the impressed voltage of the circuit, consequently a spark passes without causing the formation of an arc.

Under similar conditions in the multigap arrester using four $\frac{1}{32}$-in. gaps the spark voltage of a single gap may be in the neighborhood of 2000 volts and the spark voltage of the four gaps in series may lie between 5000 and 6000 volts. The electromotive force absorbed by a single arc in practice will be scarcely greater than 16 volts per gap or 70 volts total for the four gaps. The spark voltage is about 125 times as great as the arc voltage for a single gap or about 80 times as great for the total of the four gaps.

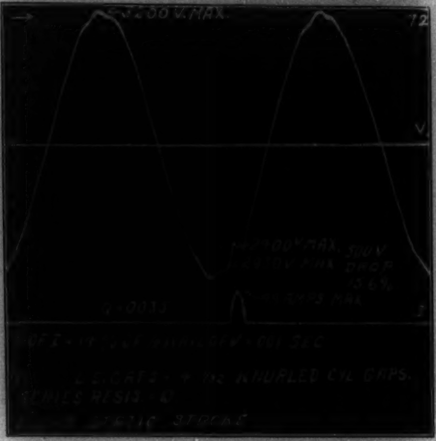


Fig. 14.—Oscillogram 72. Liquid electrode arrester using series **gaps** in conjunction with the small gaps above the electrolyte. There were two large lightning arrester choke coils of the pancake type in series. These choke coils give the exaggerated drop of potential (500 volts) at the instant of discharge.

Herefrom it follows that the multigap arrester does not work on the principal of counter electromotive force but upon the principal of rectification. The arrester is therefore suitable for alternating-current circuits but not at all adapted to direct-current circuits. When the currents attempt to reverse at the beginning of the second half-cycle, several hundred or even thousand volts may be required to cause the reversal. During the first half-cycle there is little obstruction to the current flowing in the arcs of the gaps, and therefore it is necessary to have an artificial resistance in series to limit the dynamic current.

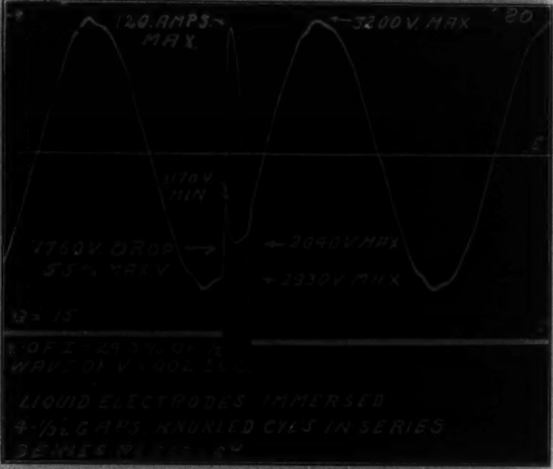


FIG. 15.—Oscillogram 80. Liquid electrode arrester with immersed terminals. The heavy lightning arrester choke coils are in series. These reactance coils add to the line drop of potential. This oscillogram shows a method of obtaining any desired quantity of dynamic discharge before the interruption of the current. The current has increased from 0.4 ampere (Fig. 12) to 120 amp. maximum due to the immersion of the metal terminals. In spite of this heavy current discharge the current decreases to zero before the potential reaches zero. Compare this to the results in Fig. 5 where the potential reaches zero and reverses before the arc is extinguished.

A liquid electrode arrester set with four gaps of equal value to the above mentioned case will have a spark voltage of 1⅓ times as great as the electromotive force absorbed by the arc, considering a single element only or about 1.8 times as great considering both cells. On a 2300 (effective) circuit the maximum voltage is about 3200 volts. The maximum arc voltage of the two cells containing a particular electrolyte is about 3000 volts. A spark can form into an arc only at the peak value and is extinguished long before the generator voltages reaches zero. Any voltage above 1500 volts per cell produces a rush of current in proportion to the pressure above 1500 volts. In other words, the cell has a critical voltage above which there is a free discharge of electricity without the intervention of anything more than a slight ohmic resistance. In the foregoing explanation only general considerations have been held in view. Some of the experimental data from which the conclusions were drawn are given later in the form of oscillograms.

Fig. 16.—Oscillogram 334. Liquid electrode arrester with the metallic electrodes slightly in contact. The upper curve, the potential wave, is only slightly distorted. The middle curve, the current wave, rises rapidly to 37 amperes and diminishes gradually to zero. The lower curve, the potential across the cell, rises with the same abruptness as the current wave, maintains a constant value while the electromagnetic energy of the circuit is discharging and then drops quickly to zero when no longer required to oppose the current discharge.

Electrodes in Contact.—When the metallic electrodes touch the liquid it is necessary to introduce a single gap in series to hold back the line potential. Since the counter electromotive force of arcs in the arrester limit the current, this single gap suffices even at the high potentials used on long-distance transmission circuits. A simple arrester circuit is shown in Fig. 8. The series gaps may be set at any value above line potential. When the potential breaks across the gaps the current begins to discharge at short-circuit rate. The current density at the electrodes is such as to start an arc which throws the electrolyte away from the electrode and automatically

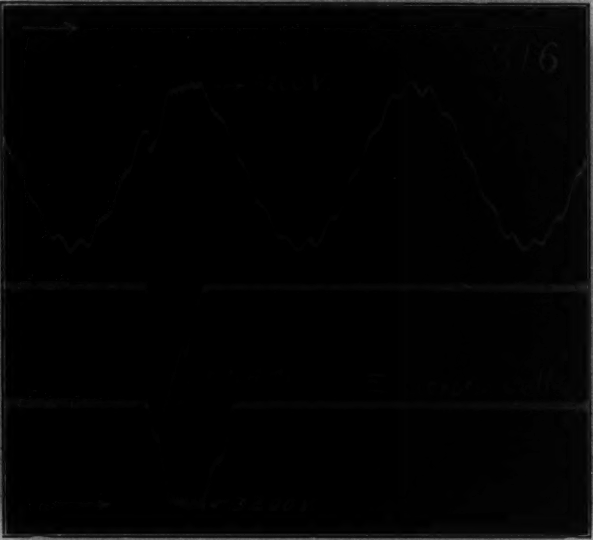


Fig. 17.—Oscillogram 316. Liquid electrode arrester with the metallic electrodes in contact with the electrolyte. The static discharge takes place on the rising part of the potential wave. The drop in the upper potential wave is due to the inductance of the circuit. The potential wave quickly recovers its normal form. The current reduces to zero in advance of the potential. The potential across the cell reduces to zero with the potential of the generator wave. The maximum counter electromotive force of the cells is equal to the impressed voltage of the circuit.

lengthens the arc. The arc voltage is greater than the impressed voltage and consequently the current dies out. The series gaps hold back the line voltage and the electrolyte assumes again its level in contact with the electrode. The current starts on short circuit but decreases so gradually that no surges have been detected either by the oscillograph or by parallel needle gaps. Extensive experimental tests have been made on a commercial circuit of 2300 volts, 13,000 volts, and 33,000 volts normal voltage. The last mentioned circuit consisted of 30 miles of three phase line and was subjected to surges due to numerous arcs drawn out between a phase and ground. These arcs to ground attained maximum lengths of five feet.

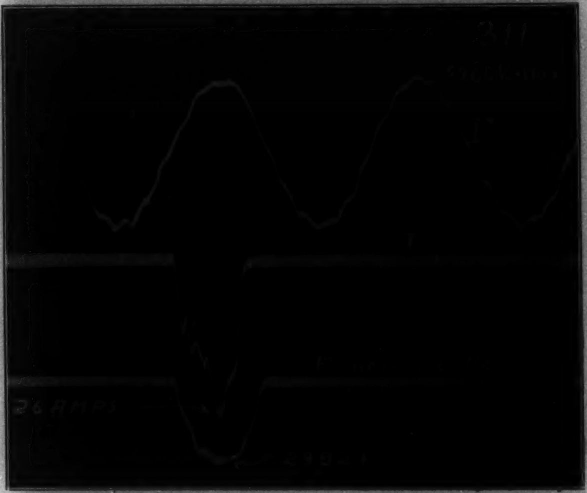


Fig. 18.—Oscillogram 311. Liquid electrode arrester with the metallic electrodes in contact with the electrolyte. The spark takes place near the zero value of rising potential, consequently the rise in current and potential across the cells is more gradual than in the previous oscillograms.

The arc voltage of the liquid electrode depends somewhat upon the length of the arc. Since it is the current which depresses the surface of the electrolyte, the length of arc depends greatly upon the value of the current. As the current decreases the electrolyte rises toward the metallic electrode. After the first instant the phenomena are of the nature of cushion effects.

The quantity of electricity which passes through the arrester before the electromotive forces absorbed by the arcs becomes active depends upon the amount of surface of metallic electrode exposed to the liquid. This value can be increased by immersing the metal to a greater depth.

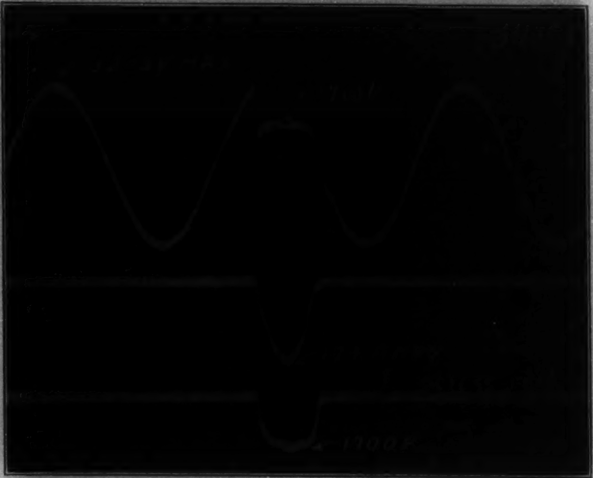


Fig. 19.—Oscillogram 340. Illustrating the critical limiting value of cell voltage. There is but one cell on a 3200 volts (max.) circuit. The spark takes place at about 3000 volts and the potential drops to 1700 volts and remains sensibly constant during the rest of the half-cycle in spite of the capacity of the generator to which it is connected. The current rises to 174 amp. maximum. This cell acts as a short-circuit for pressure above 1700 volts, but is active in opposing the current flow as soon as the pressure falls again to 1700 volts.

The ohmic resistance of the arrester is located initially in the liquid only but gradually divides between the series arc and the electrolyte. The electrolyte is a large body of large cross-section and low specific resistance, and therefore the resistance is very low.

The electromotive force absorbed by the arc at the electrolyte varies somewhat with the nature of the electrolyte.

Although the initial current may be considerable, the total current in continuous operation is not. To determine the endurance of the arrester, a 13,000-volt unit was connected to one phase of a circuit without any series gap or resistance. This circuit consisted of a 2000-kw. generator connected to nearly a mile of cable and seven miles of overhead line. The other two phases

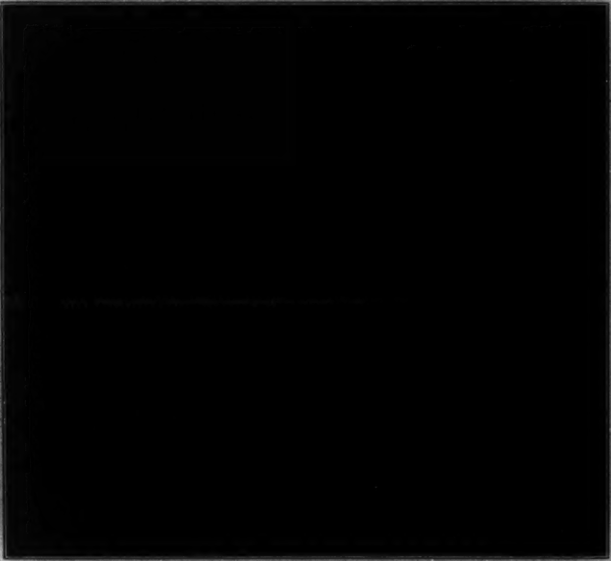


FIG. 20.—Oscillogram 351. The recovery of a liquid electrode arrester after a lightning discharge. The upper wave is the potential across the entire arrester. The lower curve is the potential across the series gaps alone. The middle wave is that of the current of discharge. The actual wave is not visible on account of poor illumination of the mirror of the vibrator, but the duration is shown by the open space in the zero line of current during the third cycle after the opening of the shutter. The potential curve across the gaps shows a drop to zero, then a gradual recovery to full line potential. During this interval the arrester is ready for a second discharge.

were protected by gaps set at 150% of line voltage. The potential of these phases did not jump the gaps during the severest tests. It should be noted that the arrester was in action under the abnormal condition of no series gaps. The action of the arcs gradually lowered the level of the liquid until 13,000 volts would no longer maintain the arcs. The time required to do this depends on the construction of the

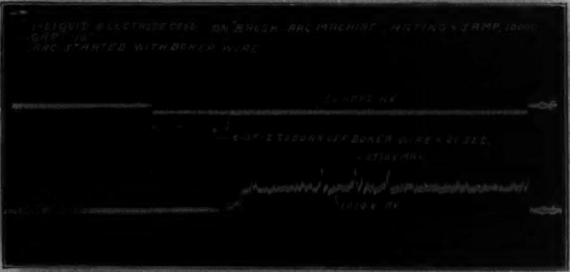


FIG. 21.—Oscillogram 117. Liquid electrode cell on 3.6 amperes constant current. The voltage varies considerably due to the splashing of the electrolyte. The small lumps in the current wave are due to the irregular intensity of the oscillograph arc. The average voltage for this electrolyte and current is approximately 1000 volts. The arc was started by means of a 5 mil Boher wire. It required 0.2 sec. to burn off this fuse with the current at 3.6 amperes.

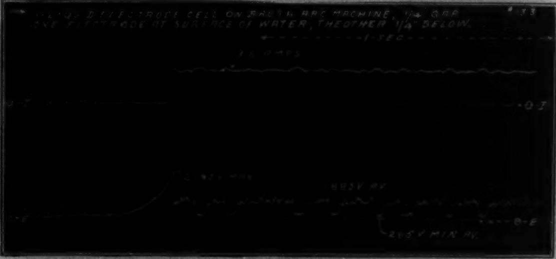


FIG. 22.—Oscillogram 133. Liquid electrode cell on direct current showing the time required for the arc to bore ¼ inch below the surface of the electrolyte. The average potential with the liquid as the negative electrode in 885 volts, but when the arc reaches the metal electrode in the liquid the voltage drops to 285 volts or less. Shortly after the liquid again sweeps over the lower metal electrode and raises the voltage again.

cells. In the small cells it is about five minutes and in the large cells somewhere between ten and twenty minutes. This time can be increased if found advisable. This sustained operation should make the liquid electrode arrester suitable to take care of the recurring surges on an isolated delta or Y system, when one phase is grounded through more or less of an arc, during a time amply sufficient to disconnect the faulty line. In the foregoing experiment a 20-ampere fuse in series with the arrester was unaffected. Apparently the possibility of an interruption in practice due to the short circuit of the arrester can be eleminated as it was in this test.

In practice the number of cells would be chosen to give a critical limiting voltage of 125% to 140% of the impressed voltage. The gap length may be set to give any desired protection. Since the arrester has but a single gap, the spark potential is as near independent of the natural frequency of the lightning surge as possible. It should discharge with facility low-frequency surges. It has a small dielectric spark lag.

FIG. 23.—Oscillogram 136. Potential of a horn gap discharging 36 amperes constant current. The arc rose up the horns with considerable difficulty. The arc would flame to a peak and the potential would strike across below the peak and thus shorten the total length of the arc. The shortening of the arc would drop the potential. This effect is shown in the lower curve of the oscillogram by the repeated drops in the potential. The arc held in the narrow gap for about a second. This is shown by the low voltage of the curve. The total time the arc held was two seconds.

The characteristics of the liquid arrester have been studied in detail with the aid of an oscillograph. A few oscillograms have been chosen which show the effect of a cell on the current and potential of a commercial 2300-volt circuit. Among other things shown in these oscillograms are:

The effect of discharge at different points of the potential wave.

The effect of more or less immersion of the metallic electrode on the current and potential.

The critical limiting voltage of an electrolyte.

The critical limiting voltage of the arc in the standard multi-gap arrester (this is given for comparison).

The initial short-circuit effect and subsequent cushion effect.

The recovery of the cell after the discharge.

The reduction of current to zero before the potential wave reaches zero.

The writer pays his grateful homage to the originator of the oscillograph M. André Blondel. The value of the oscillograph in this work will be evident from an inspection of the oscillograms. The auxiliary apparatus necessary to get initial effects of discharges is quite essential. The problem is to place on a revolving photographic film with a total time of exposure of about 1/10 second, a static spark which will start the dynamic current flowing at any chosen point of the potential wave not varying in location by more than about 1/1000 second. In the following described combination of switches the operations are entirely automatic. It requires only the release of a latch. The oscillograph is so constructed

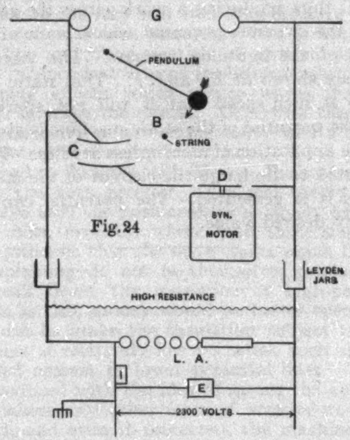


Fig. 24

that a lever operates the shutter. The shutter is opened by the lever and closed by a complete revolution of the drum carrying the photographic film. Fig. 24 shows the connections and locations of the apparatus. When the pendulum is released it strikes a string at *B* which opens the kodak shutter; it then closes the circuit between the two parallel strips during an interval depending on the velocity of the pendulum and the length of the strips. Meanwhile the synchronous motor carrying the synchronous switch at *D* closes the circuit of the static machine located at *G*. This release of the potential on the inner coatings of the Leyden jars throws the potential on to the lightning arrester *L A*, thus producing a spark across the gaps. An arc follows from the dynamic potential which is also impressed on the terminals of the lightning arrester. The vibrators of the oscillograph are shown at *E*, and *I*. The static machine is kept running at such speed that it will not spark across the gap at *C*. The potential of the static machine is also easily controlled by the application of more or less needles. These needles can be regulated to discharge the current of the static machine as rapidly as it is generated. The potential can thereby be limited to any desired value.

DISCUSSION ON "LIGHTNING PHENOMENA IN ELECTRIC CIRCUITS", "PROTECTION AGAINST LIGHTNING, AND THE MULTIGAP LIGHTNING-ARRESTER", AND "NEW PRINCIPLES IN THE DESIGN OF LIGHTNING-ARRESTERS", AT NEW YORK, MARCH 29, 1907.

F. A. C. Perrine: Dr. Steinmetz gives a clear description and classification of the lightning phenomena that aid us greatly in understanding the problems and the methods proposed for meeting them. They are, however, the simple problems; there is yet to discuss what occurs when two sets of waves started from different points on a long transmission line eventually come together. Aside from the increased constants (capacity and self-induction) I think there will be additional difficulties, due to the fact that in a long-distance transmission line traversing a great area there may be a storm at a certain part of the line and clear weather at another part; or there may be two independent storms in different parts of the line, giving lightning effects which induce waves that meet and combine, and increase the effects. Otherwise there would not be so much difficulty in protecting fairly well a long and extensive low-potential distribution system.

I am inclined to disagree with Messrs. Rushmore and Dubois in regard to the horn arrester. The real theory adopted by those who have used the horn arrester is largely left out of this paper. The horn arrester, where used successfully, has been used on the principle that the wave trains which Dr. Steinmetz has been explaining do not in themselves produce potentials that will break down the insulation of high-potential lines. The principle is that money would be better spent in erecting lines so as not to make the insulation subject to breakdown by wave trains of relatively low potential, such as would have to be guarded against in lower potential lines. The horn arrester is introduced with the idea of saving the apparatus from destruction where any other form of arrester would not itself be destroyed, and even if protected, the machinery would lie open for damage in the further continuance of the storm. This is a condition frequently met with in the introduction of the multigap arrester even of the best form. With extreme cases, which Dr. Steinmetz has described, of the short-circuiting potential and discharge across the arresters of extraordinarily high energy, the multigap arresters generally fail and the line is then left unprotected even if the machinery is safe.

At a recent meeting of the Institute, in referring to the lightning-arrester problem, if I remember correctly, Mr. Mershon said he used three sets of horn arresters each of a different value of resistance in series. That system has had, say, a year of operation at Niagara Falls. While it has demonstrated that the system of protection is not complete—requiring for certain types of discharge that come from the line a set of multigap arresters in connection with the horn arresters situated probably inside the station—yet the horn arresters will discharge over the multigap arresters, and these high-frequency discharges are discharged over the multigap arresters harmlessly. At the same time the horn arresters discharge the low periodicity surges which are usually destructive to the multigap arrester.

I do not agree with Mr. Rushmore and Mr. Dubois that the horn arrester is better adapted for discharging high-frequency discharges. As a matter of fact the opposite is true. As stated by Mr. Creighton, the higher the frequency of the discharge the more rapidly is it carried over the multigap arrester. The low-frequency discharges are not so well taken over the multigap arrester, whereas with the horn arrester the low-frequency discharge is more rapidly taken over than with the multigap arrester.

In the present state of the art, excluding the electrolytic arrester described in one form to-night and in another form by Mr. Jackson a few months ago, I think the best protection is a combination of the horn and multigap arrester; the multigap arrester to take charge of the relatively high-frequency discharges, and the horn arrester to take charge of the low-frequency discharges.

I think that the construction of a polehead to take care of the overhead ground wire is open to criticism. In the first place, the pipe is an extremely bad piece of engineering. The connection to the pole is not good, for the amount of leverage shown is excessive; and I confess that for the present I cannot see how a workman is going to attach a ground wire, ⅜-in. in diameter to the top of the pipe, unless there is some means provided for hauling up the wire to prevent the dead-end from being pulled over.

As regards the guard-wire put on the arm, as a horn arrester to protect the insulator, I cannot see how that particular form of arrester will do other than hold the arc. If an opposite horn were brought out from the line, and a horn arrester made there, it would discharge and protect the insulator In the same connection the authors speak of the specification for this overhead wire. I have always believed that a barbed wire, if made properly, is a better means of line protection than a smooth wire; at the same time I question very much whether a satisfactory barbed wire arrester can be made. I prefer a three-wire ¼-in strand of high grade steel to a ⅜-in. stranded steel.

The treatment of the multigap arrester adds to our knowledge of the manner of action of this bit of apparatus. Mr. Creighton explains particularly the influence of the rectifying effect of the non-arcing metal (to refer to Wurts' term). The capacity effects described in the paper by Messrs. Rushmore and Dubois are simply in addition to the effect of the series resistance or shunt resistance, and in addition also to the rectifying effect of the metal in the gaps--and metal which will rectify is absolutely necessary for the success of the multigap arrester. Mr. Creighton explains in an interesting way the function of the resistance in connection with the multigap arrester. He calls attention to the fact that there is really no radiation from the resistor in such an arrester; and in forming such resistor there must be taken into account the specific heat of the material and the extent of the metal, so that it may absorb the energy. At this time, and I believe for the first time, our attention is called to the fact that the radiation of the resistor is relatively unimportant

We seem to have here an entirely new form of electrolytic arrester. The principle Mr. Creighton describes is of actually striking an arc in the electrolyte, and so obtaining the benefit, as a resistance, of the counter electromotive force of the arc is very important indeed. We all know what Edison said of his storage-battery: "The damned thing is wet." This apparatus is not only wet, but it relies for its action on the formation of an arc within the arrester, which I should suppose would very rapidly evaporate the electrolyte, and the cells would require considerable watching in order to keep the electrolyte at a·certain level.

As Dr. Steinmetz has aptly said, lightning-arrester problems cannot be efficiently studied in the laboratory. At the same time our somewhat restricted methods of work in the laboratory can better be explained and extended to practical use by means of the oscillograph than by any other means. The laboratory work on the electrolytic arrester of Mr. Creighton is of great importance, particularly because he shows his arrester as a single-gap arrester; in other words, a horn. At the same time he shows how the horns can be set close enough together so that they will take care of the high-frequency, low-potential discharges as well as the low-frequency, high-potential discharges; this gives practically a single horn arrester with a variable resistance in series, which is all that the horn arrester needs in order to become the best arrester that can be made. Furthermore, the electrolytic arrester puts what amounts to practically a variable fuse in the circuit, as well as a variable resistance, and it gives also a replaceable fuse. In my mind the need of the fuse is the greatest criticism that can be made of the arresters shown by Mr. Rushmore. All these arresters have fuses in them. If they are meant to blow, I feel quite sure that all operating men will agree that in a serious thunderstorm, such as occurs in the South or in the Colorado region, they will never be replaced after they have once blown during that storm. I do not know of any man with nerve enough to go near an arrester to put in a new fuse.

This substitution of a variable resistance, counter electromotive force, and a replaceable fuse and single gap arrester which is described by Mr. Creighton, is, in my mind, the practical solution of the lightning-arrester problem. I believe if this is worked out commercially we will be much nearer the complete solution of this problem than we have ever been before.

Farley Osgood: I will not attempt to discuss the papers individually, but will endeavor to contribute some corroborative evidence concerning the problem as a whole. Experience seems to show that lightning protection is an individual study for each individual plant, and for each individual locality. In talking with other operating engineers, I find that they use quite different methods of protection from the ones we use and they are equally successful or unsuccessful. Each man seems to have his own ideas about it, so I think that the lightning-arrester problem, like some of our other problems, is going to be a rather difficult one to standardize. I do not think the difficulties of atmospheric conditions are so very serious, generally speaking. Dense fog causes most of the trouble to our outside system; during other times we seem to get along without difficulty.

I will now relate some actual experiences occurring in a 33,000-volt transmission system, of 60 miles, carrying three substations, with power and lighting load, and 60-cycle synchronous converters. The multigap arrester with the resistance in series with the gaps, was used in 1904 and 1905, and was finally given up because the series resistance sticks broke and the protection was lost. The next year we took up the multigap arrester without the resistance sticks in series. This arrester, as can be seen from the photographs here, was very easy to adjust by changing the units to be shunted and changing the resistance of the shunt. We started with 14 units of 24 gaps each, shunting three units with 14 sticks, 250 ohms per stick. This equipment was gradually reduced until we used 10 units, to the multiple connection between the phases, and ten units below the multiplex, shunting 5 units with seven 250-ohm resistance sticks. We found by the tell-tale papers that with seven 250-ohm resistance sticks the current would seldom pass through the shunt resistance. We reduced them to five and then found that we got at least half the discharges through the shunt, sometimes more. This arrester, adjusted in this way, has been successful. It takes light discharges without the slightest difficulty; it takes moderate discharges with but very little difficulty; it takes very severe discharges at times, but these severe discharges are apt to cause the cylinders of the arrester to weld together, which of course puts the arrester out of service.

Another thing that has been noticed is that the discharge is more frequently line to line than line to ground. The 1906 record shows that we have taken in some storms twenty discharges without an interruption to service, our time-limit breakers being set at six and a half seconds. We have taken 17 discharges without interruption, the eighteenth discharge opening the breaker. I could cite case after case of storm in the surrounding country, but not directly on the system, where there were intermittent discharges between the phases to the extent of fifteen, or even as many as twenty-five in the course of two or three hours, without the slightest indication of interruption. This is the best record we have been able to obtain with protective devices.

Mr. Rushmore and Mr. Dubois speak of choke-coils. We have found them very effective, and consider that they are a great protection to the high-tension bus-bar insulators. A 20-turn coil 6 in. in diameter made of 00 copper seems to answer our purpose fairly well.

Dr. Perrine objects to the electrolytic arrester on account of its being wet, but I see no reason why it should not be made water-tight.

I do not wish to talk very much about Mr. Creighton's tests, although it was my pleasure to be present at the time they were made. I can simply corroborate what he says, that some 40 arcs, five feet in length, were drawn by grounding one phase wire just ahead of the liquid arrester. The multigap arresters just described, the record of which just given shows that they are very sensitive, were in parallel with the liquid arrester. Not once was there any apparent discharge on any of the units of the multigap arrester. These tests were made with 30 miles of circuit cut in.

Dr. Perrine speaks of the length of the transmission line having a great deal to do with the matter of protection. That seems to be true. In our experience we found wave peaks developed between stations, which do much damage before the arresters at the ends of the line begin to help out. We installed what we call our midway arrester, a multigap installation about 10 to 12 miles from the power station. Immediately after this was put into service the constant static discharge on the power station arresters and the sub-station arresters was cut down nearly one-half, and the constant static discharge at the midway arrester was greater than at the generating station or at any of the sub-stations. That seems to be fairly good proof that arresters on the line are a good thing. For the benefit of other operating engineers, I might state that this arrester equipment is very near the patrolman's house, so that it is easily controlled.

One great trouble in following the study of arresters is to get definite information concerning the action of the arresters. We do our best with tell-tale papers, but it is very often impossible to replace a tell-tale paper after a discharge comes, for another discharge comes so soon and operators have other things to do besides watching the arresters. Our tell-tale papers burn up during severe storms, and this destroys our records completely. I would suggest that a tell-tale paper which would not take fire but which could be prepared to show a puncture, would help us to obtain better records. It is a difficult matter to get the operators to realize the importance of following every lightning storm, to the extent of counting the number of discharges, but if proper forms are made for this purpose I see no reason why the study cannot be carried on without great difficulty.

The worst operating condition we have to meet is that due to grounding. More damage is done when a phase grounds than at any other time. I am not prepared to say that grounds only are responsible for the destruction of apparatus, but more apparatus is destroyed when there are grounds than at any other time. Mr. Creighton's liquid arrester, which was connected for the protection of grounds on the system, apparently solved the problem completely. The development of the liquid arrester brings out the fact that at least for grounds it may be necessary to have arresters only at the generating end of the system, or at least at the extreme ends, with no equipment in between. The power of self-restoration of the electrolytic arrester is one of its most beneficial qualities.

P. H. Thomas: It is interesting to note that most engineers are in agreement in the matter of protecting apparatus from damage by lightning. The multigap arrester with shunt resistance, ignoring the electrolytic arrester for the present, seems to be the most promising direction in which to work. The differences in commercial designs now are comparatively small.

In general I agree with nearly all that is said in these papers, but there are some things still open to an honest difference of opinion. Unfortunately, it is necessary to emphasize the things we do not agree with, even if they are not so important as some things we may approve of.

I do not know that I agree with Dr. Steinmetz's new definition of lightning. We must of course recognize the fact that an arrester is not only effective, if it is effective at all, against lightning, but also against the other sorts of static disturbances; but if we want a general term, rather than change the time-honored significance of "lightning," I would suggest the word "static," which has been pretty generally used. Another thing which does not appeal to me is the analogy that Dr. Steinmetz makes between electrical wave phenomena and the surf of the ocean. The reference to surf presumably means the dashing of spray which results from the pounding of the water against a surface, either the horizontal surface of the beach, or the overhanging surface of a rock. As we all know, in the electric circuit capacity is analogous to the spring or to elasticity; that is, the freedom of the water of the ocean to move upward in the analogy. Self-induction is analogous to inertia. The analogy of the splashing of water, where it strikes *against* an opposing surface, is the breaking, or instantaneous stoppage of the flow of current; it is in the nature of the Wehnelt interrupter, or the low-tension break in a Rhumkoff coil. The phenomenon in a transmission line, when a wave meets a reflecting point, is truly analogous to the wave in the water reaching a perpendicular smooth wall; the wave will rise to double the height, but there will be no splashing—a plain, simple vertical rise. If the wave be in a trough of water, and the trough tapered off to a point, and the taper commensurate with the length of the wave, there will be a rise of potential, but not a splash; a normal, straightforward rise. There is evidently no break in the continuity of a transmission circuit on the reflection of the electric wave.

I am more inclined to agree with Mr. Rushmore than with Dr. Perrine in connection with the horn type of arrester. I think we are far enough advanced to protect our apparatus without the very annoying disturbances of shutting down the plant. The grounded wire is certainly some protection, but, as Mr. Rushmore says, not complete protection. One of the difficulties, even if the wire is placed directly overhead is that the discharge which strikes the line is more apt to come from the side. Coming thus, it approaches one of the side wires before it does the grounded wire, and there is frequently recurring on these lines alternately positive and negative potential, which will tend to draw the discharge to one of these wires from the ground wire. It is often suggested that a grounded wire, if it be grounded frequently, will act effectively in reducing the severity of discharges, on account of the short-circuiting secondary action. It does not seem to me probable that the effectiveness of this action will be at all considerable, and for this reason—to produce any corrective effect the reaction of the induced current on the primary circuit must be considerable. Take an ordinary static transformer, where the reaction of the secondary on the primary is virtually perfect. To accomplish this result it is necessary to have an iron core and the closest relationship between the primary and secondary windings. In the constant-current regulating transformer, where there is provision to separate the windings, if the coils are close together, there will be a nearly perfect relationship between the primaries and secondaries, and a nearly perfect reaction of the secondary on the primary. But if the secondary is separated from the primary, the effect of the secondary on the primary is almost negligible.

In his admirable discussion of the principles covering the discharge through a series of gaps, there was one thing Mr. Rushmore did not take into account, and that is the fact of the leakage of current over the surface of the insulator between the cylinders. This will tend to distort numerically the conclusions reached. If this phenomenon gives trouble in designing arresters, it is easily controlled by placing a considerable gap in series with the arrester, between the lines and the first cylinder. or by using a shield connected to line. A great deal of stress has been laid on the fact that in virtue of the resistance adjustments the arrester Mr. Rushmore has designed will not break down on lower voltages at high frequency, than at a low frequency. Offhand, I do not see why if a high-frequency disturbance will go to ground more readily than a low-frequency disturbance, it should not be permitted to do so. If this resulted in a too frequent discharge of the arrester, it would be harmful, but our experience does not appear to indicate that such is the case.

The term "rectification of vapor" has been used several times to-night to explain the non-arcing property of a multigap arrester. The significance of this term I cannot quite understand. Vapor consists presumably of an aggregation of atoms or molecules, and since the atoms or molecules move freely in an entirely accidental manner, I cannot understand how this vapor of itself can have any directive effect. I think the action can perhaps be explained in the following manner: it is pretty well agreed that an arc starts by the ionization, through potential strain, of the gases between the electrodes, by which ions are liberated. They are then forced to move extremely rapidly by the high potential and produce other ions, until finally there is such an increase of temperature and such an increased ratio of ionization, that the quantity produced is sufficient to carry the normal arc current at a low voltage.

It is now easy to imagine in these narrow gaps between large cylinders in the multigap arresters that when the discharge comes along, ions are produced in this way, but that the instant the discharge and normal current ceases at the end of an alternation, in view of the close neighborhood of the conducting cylinders, the ions which would otherwise hold over until the return of the voltage are freely absorbed by the metal. The fact that an easily vaporized material is used in the composition of the cylinders will keep down the temperature; and since ionization is very closely related to temperature, the high temperature very much increasing the ionization, this effect will account for the properties of different materials. The current is of course carried by the movement of the positive ions to the negative pole, and the negative ions to the positive pole.

I would like to ask Mr. Creighton whether in his tests the results are based on anything more than the work with the 2300-volt outfit described here? that is, whether higher voltages or larger powers were used?

E. E. F. Creighton: We have taken some measurements at higher voltages, but we have not made as complete a study of them as in the case of the 2300-volt machine.

P. H. Thomas: The question of power behind the tests is absolutely of importance in this sort of work, and inherently the higher the voltage the more difficult to handle. Personally I should be very skeptical of the general non-arcing quality of this arrester without series resistance, and unless there are other data than what appears here, I should not suppose it would be safe to infer anything as to its general non-arcing quality. We find in one of the oscillographs, Fig. 4, that 200 amperes absolutely cuts the generator voltage down from 2,000 to a few per cent. of this value, showing a very limited capacity of power behind the arc. Similarly with Fig. 5.

V. G. Converse: Having installed at the plant with which I am now associated a considerable equipment of horn-gap arresters, I may perhaps be expected to take exception to the comments made in Mr. Rushmore's paper regarding this arrester; on the contrary, I quite agree with him. However, Mr. Rushmore states:

> Where a fuse is used in series with a horn having no resistance, it can, of course, take but the one stroke, and after this the system is unprotected.

This objection can be overcome by the use of repeating fuses arranged so that if one fuse blows, a switch drops, connecting in a second fuse; if the second fuse blows, a third is connected by a switch, and so on. If the fuse is of a proper enclosed form, it in itself very nearly meets Mr. Rushmore's requirement for the ideal arrester; but such a device may not be termed a horn arrester as the horns are no longer necessary.

Mr. Rushmore further says:

> The real function of the horn arrester is its use to protect insulators along a transmission line, where the horns are so arranged that the current will jump to the horn before it will arc around the insulator. In this case the system would be disturbed either way. Where it is allowed to arc around the insulator, the latter would probably be destroyed and the time of disturbance of the system might be considerable—possibly until the insulator is replaced. With a horn protecting the insulator, the resulting short-circuit, while very undesirable in itself, is less disastrous than in the former case, and may only necessitate starting up the synchronous apparatus again.

From my experience, and I believe that it will be found to be the experience of others, the principal lightning troubles on a high-tension system are stated in those few sentences. The Ontario Power Company during the whole of the last season had only one discharge of consequence over its arresters at the generating station, but had a considerable number of discharges along the lines, which caused interruptions of service.

The lightning-arresters described in these papers are essentially station arresters, and while it is gratifying to learn that satisfactory results are promised for this purpose, it should not be overlooked that for continuous operation, line lightning protection is also of great importance, for which other arresters are required.

D. Dubois: In regard to the breakdown of the high-voltage arresters at a low-frequency power surge, a little more should be added. As the voltage rises, and before it reaches a dangerous value, the gaps G_2, Fig. 3, arc over. As explained, the voltage to break down these gaps must be higher than if no resistance were used in series. With these gaps broken down, the current of the arc across them is limited by the high resistance to about $\frac{1}{16}$ ampere, which gives about 80 volts drop per gap. The remainder of the voltage is consumed in drop across the resistance rods and is thus applied across the gaps G_h. Although this voltage is less than that which broke across G_s, the series resistance is less, and approximately the same number of gaps will therefore break across at this lower voltage. With G_s and G_h broken down, the increased current gives a smaller drop in the gaps, but twice the number of arcing gaps are now in series. Therefore the number of gaps in G_m is made the same as in G_s and G_h. These three sections should all arc over in succession at very nearly the same voltage.

In this arrester the different kinds of lightning will follow different paths through the arrester, and test papers should be more useful than ever before in determining the nature of the discharge. Test papers should be placed in all four divisions of each line leg, and in the three divisions of the ground leg. Designating the different divisions as in Fig. 33, G_s, G_h, G_n, etc., the different kinds of lightning should produce punctures and burning as follows:

Static charge of the line relieved or a very light discharge—G_s small slightly burned pin-hole, others not touched.

Low-frequency surge of small power, or discharge of medium frequency—G_s and G_h small burned holes, others not touched.

Low-frequency power surge, or abnormal rise of power voltage—G_s, G_h and G_m well burned holes, G_1 not touched.

High-frequency discharge of the arrester—G_s and G_h small burned holes—G_m and G_1 punctured, but not burned.

The test papers of the ground leg can show whether the discharge took place from line to line or from line to ground, and whether the line became grounded during the discharge.

Wm. McClellan: While deciding on the lightning protection for a sub-station which takes current at 60,000 volts and delivers it at 11,000 volts to a trolley line, we were impressed with the well-known fact that the selection of lightning protective apparatus depends on the amount of power back of the stroke and the voltage of the line to be protected. For the 11,000-volt circuit a form of multigap arrester was used. Perhaps some of these multigap arresters are better than others, but any well-designed one will answer for low voltages. The small amount of lightning that we have had this year has burned the gaps somewhat; this we know is the chief difficulty in connection with the multigap arrester. For the 60,000-volt lines, outdoor arresters of the horn type were used. There are three horns on each leg of the three-phase circuit. In series to ground with one of these horns is an enclosed indicating fuse 6 ft. long; this fuse works very definitely and positively, although it has not yet operated in connection with lightning discharges. A second horn has in series to ground a resistance made up of concrete blocks. The third horn has in series to ground one of the electrolytic arresters described by Mr. Jackson several months ago. It is hoped to show that the electrolytic arrester will take care of all discharges through the lightning season. If this proves to be true, increasing experience will warrant us in discarding all other types and depending solely on this type of arrester.

Such an arrester is in the nature of a safety-valve. As soon as the pressure rises to a certain critical point, it provides a free path of very low conductivity to ground; and when the accidental pressure on the line is relieved, the arrester comes back to its normal resistance. Such an arrester will be operated with a gap in series just large enough to prevent the normal voltage from breaking over. A horn in this case is entirely unnecessary, since the arc is opened by the small arrester current after the accidental high voltage is relieved.

I agree in general with everything that is said in the paper in regard to the horn arrester, but I do not believe in an arrester consisting of various horns with graded resistances. When extra turns are put on the transformers and powerful insulators on the line, all designed to take care of the certain rises in voltage, there seems little use in applying horn gaps with high resistances in order to relieve the line of rises in voltage slightly above normal. I think the horn arrester has been found useful only in those places where there is sufficient power back of it, so that the current passing over the horn is not large enough to shut down the station. In other words the horn type is successful in those few places where one can wait for the horn to open the circuit. It should be remembered, however, that under certain wind conditions, and also if the horn is not correctly shaped, it may be an excessively long time in opening the discharge circuit.

My faith in the electrolytic arrester has grown, so that for circuits of approximately 11,000 volts I would be inclined to use this arrester indoors; for circuits of approximately 60,000 volts I would use the electrolytic arrester also, with or without a horn, supported, however, as a last resort by a sturdy gap with enclosed fuse in series to ground. Such an enclosed fuse containing a No. 30 copper wire will open the discharge circuit in less than one cycle, whereas from 30 to 60 cycles is the usual time for the horn type under the best conditions. With either, on all circuits, choke-coils should be used beyond the arresters.

R. P. Jackson: Regarding the non-arcing quality of the so-called non-arcing metal: Mr. Rushmore, I believe, ascribed it to the boiling point of certain elements in the alloy. I think one thing has been lost sight of. Years ago, when Mr. Wurts first made the discovery of non-arcing metal, he found that there were certain metals belonging to one group that had that quality to a large degree, and other metals did not have that quality to any considerable degree or to any degree at all. These metals were cadmium, mercury, and zinc. They are all monatomic; that is, their gases are formed of molecules of one atom. This has a very important relation to the non-arcing quality, in that the gases have twice the volume that gases from other metals have. Also it is highly probable that a comparatively small number of ions will exist in the gases. Therefore, there would be much less chance for the arc to establish or maintain itself, and possibly a much greater local pressure when the spark occurs in the gap; that is, when the spark passes there will be between the surfaces of the metal a momentary great rise of pressure.

In regard to the "ideal" arrester, I think that it must be considered as a reasonable development from previous arresters used. The original non-arcing metal consisted of a single row of gaps. It was found several years ago that double the number of gaps, with half of them shunted, would form an arrester of the same equivalent as the original gaps. This can be extended, adding more resistances and more gaps, gaps being shunted by the resistance; but the equivalent begins to rise, and if another step is added, it rises somewhat more, and soon gets to a point where nothing is gained. There is not very much to be gained from more than the one step; but the equivalent will not rise quite so rapidly as the number of gaps themselves. The explanation seems to be that there is a time-period in the breakdown of the gaps; that is to say, they are not simultaneous, but consecutive.

Fuses are very good devices where they are properly arranged. In several places I have tried a fuse in parallel with the series resistance of an arrester. Such fuses will perhaps blow once or twice in a season; but when they do blow, they are badly needed.

Regarding the horn arrester, I am not sure that the rising of the arc is due to magnetic effect. Experimentally I have not found that true. I understand that at the Ontario Power Company's station the horns were arranged with coils to increase the magnetic effect, without much gain being found. I think the virtues of the horn arrester lie chiefly in its mechanical characteristics; it is comparatively simple and cheap. It has some non-arcing or arc-suppressing quality, but it has no such arc-suppressing quality as the multigap arrester. If something can be put in series with it that does not offer great impedance to the discharge of lightning or other energy, it may become useful.

The electrolytic arrester, so far as I have been able to learn, has just the characteristics that Mr. McClellan describes. It has a certain equivalent that is controlled largely by Ohm's law. If the area of the plates or the electrolyte is increased, the equivalent is decreased. If the length of the electrolyte is increased the equivalent is increased, and that equivalent seems to have comparatively little relation to the volume of discharge through it, so that it seems possible to predetermine the voltage which could escape through the arrester and simply short-circuit everything above that. In the type of electrolytic arrester which I have used, however, I do not consider it to be the counter electromotive force that limits the power current; there seems to be a dielectric film, and that film is capable of puncture and also capable of resealing when the voltage drops below a certain point. It acts like a valve with a spring behind it. When the film is punctured, if the excessive static voltage exists long enough, there will be a very large power current flowing through, but of course the high voltage due to lightning or surges exists for a very short interval, so the power that follows is insignificant.

C. P. Steinmetz: Omitting the fuse shunting the gaps requires that the gaps be always left in circuit, so that after the fuse blows there is still the same protection to the system as there would be when no fuse is used. The fuse gives a far better protection for most of the time and under most of the conditions than would be permissible without it. This use of a fuse, therefore, is not analogous to the fuse in series with the horn arrester.

Some of the questions raised refer merely to matters of terminology and would be very interesting discussions to fill the volumes of a purely scientific body. They are of comparatively little interest to an engineering society; for instance, whether the effect of some metal cylinders discovered by Mr. Wurts, and published in his classical paper fourteen years ago, might be called rectifying, or might be due to some mysterious action of some mysterious bodies, ions, jolting around in some manner—all this is quite immaterial to me. Mr. Wurts called the phenomenon "non-arcing". Mr. Creighton finds two conditions: first, if the shunt resistance is low the disruptive discharge across the cylinder is not followed at all by the generator current; secondly, the disrupted discharge is followed by the generator current during one-half wave, but no further; that is, no reversal of the generator current can take place. Mr. Creighton adopted Mr. Wurts' term for the first condition; that is, called the case "non-arcing", where no generator current follows, and he gave the name "rectifying" to the case where the current can follow in one direction only, but cannot reverse.

Whether the non-arcing character of these metals is explained as being in one group—which, incidentally, is not quite right—does not seem to be a matter of very great importance. If I recollect aright, Mr. Wurts mentioned bismuth and antimony as non-arcing; these do not belong to the zinc group, though other metals which do belong in the zinc group are not generally recognized as non-arcing. The order of the non-arcing character of the metals as given by Mr. Wurts is the order of their boiling points. All this might be an interesting subject for a purely scientific or metaphysical paper, but does not seem to be of any particular value to us.

D. B. Rushmore (by letter): Many of the points brought out by the first speaker in the discussion are answered by a more careful reading of the paper or by the other speakers.

It is agreeable to find that the statements made concerning the horn arrester are in agreement with opinions held by men of such experience as Mr. Thomas and Mr. Converse.

It is stated somewhere in the paper that the illustrations showing the scheme for protection of wood pole lines are simply diagrammatic. Attention should, however, be called to the fact that the multigap arrester described in the paper is entirely new in design, and a careful reading of the action of the discharge over the multigaps will explain the difference in principle between these and former multigap arresters.

E. E. F. Creighton (by letter) : Some one has observed that the liquid electrode arrester is wet. That is true: it is the condition sought for. After having gone over a number of different methods of preventing or extinguishing an arc, I have come to the conclusion that with but one possible exception, not yet published, the liquid gives the most valuable property to the lightning-arrester.

The objection to the liquid, as suggested by Dr. Perrine, lies in the necessity of maintaining a certain level, and it might be added to keep the liquid from splashing. This is a simple engineering problem which seems to offer no difficulty in its solution. There are several solutions being tried out at the present time, any one of which seems to be practicable.

The loss of liquid through the operation of the arrester by lightning is too slight to take into account. For example, one of these arresters was put into operation three hundred times, which would easily cover a whole season's storms even in the worst locality, and at the end of the test the level of the liquid had not been lowered to any measurable extent. The energy given out by the electric current in the arc is absorbed, first in raising the liquid to boiling temperature; secondly, in the latent energy of changing the liquid to a gas; and thirdly, in the chemical energy of dissociation of the gas. To carry through this process requires a relatively great amount of energy for a small amount of electrolyte. The amount of electric energy given off from the generator is comparatively small because the current is limited by the voltage absorbed in the arc at the surface of the electrolyte. In case of continuous discharges over the lightning-arrester due to a grounded phase on an insulated Δ or Y system, the electrolyte is gradually used up until the arc distance is too great to be bridged by the surges on the line. This, as already stated in the paper, will require a number of minutes, and it will be necessary after such an operation to refill the jars with water to the original level. It should be noted that the arrester is not damaged by this continuous operation.

In considering the operation of the liquid electrode arrester, the brief and convenient term, "variable resistance" was used but it is important to distinguish carefully between the effect obtained from a counter electromotive force and the effect from a variable resistance. Although the counter electromotive force gives the same effect as an increase in resistance in reducing the current, yet it differs materially in that it reaches a limiting critical value above which it offers no further obstruction to the current flow. From zero up to the critical voltage the ohmic resistance of the cell has probably diminished although the effect of the arc is that of an increase of resistance.

Dr. Perrine's kind expression of appreciation of the work on this new cell type arrester reminds me that it was he that first recognized the value of the aluminum cell-type arrester and aided most in its development when I began working on it some six or seven years ago.

In regard to the leakage of current between cylinder and cylinder of the multigap arrester. The experience we had some years ago will corroborate Mr. Thomas's statement. Instead of using individual units of porcelain, Mr. Wurts decided to use one slab of marble with the cylinders arranged in zigzag form, but it was found that the spark voltage or equivalent-needle-gap of the same number of gaps as used previously with the porcelain units was very greatly increased. The leakage of current though the marble was sufficient to prevent the separation of the positive and negative charge on each cylinder, and the consequent resultant static induction to the next adjacent cylinder. The ten-pin or card-house effect was lost. The drop of potential across the marble was uniform, the high frequency between cylinders was lost, and many of the gaps were in a condition of partial short-circuit due to the concentration of the leakage current in the marble in the shortest distance between terminals. I still have in my laboratory an expensive board made up in this way which is entirely inoperative as a multigap arrester.

Mr. Thomas calls attention to the short-circuit current shown in one oscillogram as only 200 amperes. This I might state was under a particular condition where only one small machine was on the circuit, and the short-circuit current shown in some of the other oscillograms is more than double the value stated. By considering the condition of discharge of the new type multigap arrester it will be seen that the generator capacity is amply sufficient to give the effect that might be obtained from a machine of any capacity. When the spark takes place across the shunt gaps, the generator is producing full potential across the arrester and the voltage is not decreased by the discharge of the dynamic; consequently if the spark is going to form into an arc there is every reason for it to do so regardless of the generator capacity. Stated otherwise, if the potential of the generator does not decrease, the experimental conditions of test are correct and nothing further could be obtained by using a generator of greater kilowatt capacity. This statement is general and applies also to the tests of the liquid electrode arrester. I admit of course that if the spark does form into an arc the damage caused will increase directly with the capacity of the generator.

C. P. Steinmetz (by letter): It seems to me that the disagreement on the horn arrester is more apparent than real: it depends upon what is expected of an arrester. Mr. Rushmore defines a lightning-arrester as an apparatus capable of discharging any abnormal voltage or abnormal frequency without interfering with the normal flow of current. This the horn arrester does not do. With series resistance it is limited in discharge capacity; without series resistance it may protect the system; but it short-circuits it, so shuts it down temporarily.

Mr. Thomas' criticism of the definition of "lightning" seems justified. It is rather strange to speak of "lightning-arresters" in underground cable systems. I have not introduced this definition; but it has gradually introduced itself in practice, and so will probably stay. The proposed name "static", however, I do not approve at all. The term "static" has been used to a considerable extent, and mostly abused. Occasionally one hears of such anomalies as "static transformers," instead of "stationary transformers". If "static" means anything, it can only mean electric phenomena of such limited power as not sufficient to produce an appreciable current; that is, phenomena in which the electromagnetic component of the field is negligible compared with the elctrostatic component. A short-circuit surge which bends heavy copper bars can then hardly be called static, but the lightning-arrester should protect against it.

In my paper I have drawn analogies between electric waves, and waves in a body of water. It is obvious that such an analogy, though elucidating the phenomena, is not complete. For instance, in an electric circuit the tendency to form stationary waves or oscillations from travelling waves or impulses is very pronounced; but in a body of water this tendency exists to a very limited extent only, since in the latter case the wave length is usually only a very small part of the total wave travel. I believe that Mr. Thomas misunderstands my comparison of the breaking of a wave train at the station with the ocean surf. Where complete reflection occurs, as at the open end of a line, a standing wave is formed from the travelling wave of the same frequency. An ocean wave, rolling on to a sloping beach, is, however, not completely reflected; it is only partly reflected, while partly it rushes up on the beach. Now at the entrance to a station an electric wave train is partly reflected, partly enters, and "surf" is the result of the interference of the various reflected and transmitted wave trains. This results in the formation of local standing waves. The surf is therefore not a complete reflection, but a breaking up of the wave. In this way an ocean wave on a sloping beach, is comparable with an electric travelling wave at the entrance to a station.

As regards the damping effect of a grounded overhead wire, it appears to be obvious that a current induced in the ground wire by a wave train in a transmission line consumes energy, and thus reduces the energy of the wave train. The energy dissipated by this induced current in the effective resistance of the ground wire is taken from the energy of the wave train in the main wire, and causes the latter to decrease more rapidly. The imperfect inductive relation between transmission wires and ground wires applies only indirectly in considering this effect. Of the total magnetic flux produced by the wave train in the main wire, and surrounding the main wire, only a part interlinks with the ground wire as mutual inductive flux; probably most of it passes between the conductors as self-inductive flux. This self-induction does not consume energy, and therefore does not dampen; but mutual induction consumes energy and so causes the wave train to decrease more rapidly.

In a lightning-arrester it is of fundamental importance not merely to discharge abnormal voltages or frequencies, but to discharge them with the least possible disturbance. This means to discharge over the highest resistance, which does not yet appreciably back up the voltage by its *Ir* drop. Sometimes the volume of discharge is such as to permit no resistance whatever. The lightning-arrester must therefore have a path of no resistance to ground. A half-wave discharge without any resistance is quite a severe shock, and should be avoided. For this purpose a medium high resistance in shunt is used to take care of most of the discharges; of the discharges that are too heavy for this resistance, most are still deflected over the "low resistance" of the arrester, so as to limit the dead short-circuit discharges to a minimum. Very many discharges, however, are of such small power that a resistance very much higher than the "medium resistance" can take care of them; and it is therefore undesirable to cause a fairly large dynamic discharge over the medium resistance every time one of these very small discharges occurs. For this purpose the high resitance has been added.

Mr. J. P. Jackson explains that the non-arcing character of mercury, cadmium, and zinc is due to these metal vapors being monatomic. It is unfortunate that helium and argon are also monatomic, but are by no means non-arcing; on the contrary, they are known to have abnormally low disruptive strength; that is, they require only a low voltage to maintain a discharge.

Wm. McClellan (by letter): It has always been difficult to get a physical conception of the action of the film used on aluminum electrodes, either of the type proposed by Mr. Creighton or the one proposed by Mr. Jackson some time ago. No physical conception can be had until a great deal more is known about this phenomenon.

The writer has always conceived of the film as being electrically porous so that up to a definite pressure it held the current, but beyond this pressure the pores, so to speak, opened, allowing the discharge to pass through freely. This conception seems reasonable when one views the formation of the film and sees the gradual decrease in the number of spark discharges all over the face of it, until finally upon the complete formation these discharges cease at pressures below the critical point. This conception is suggested by the old physical experiment of the hollow gold sphere which will hold a liquid until the pressure is raised to a particular point when the liquid squirts out all over the surface.

The writer has never been able to find or hear of more than two objections to the electrolytic arresters with the large surface as proposed by Mr. Jackson. The first of these objections is the possibility of the arrester being exploded or burst by a heavy discharge, the same as a telegraph pole or tree is frequently rent. In such cases the explosion or shattering is due to the fact that the conducting path is very circuitous and narrow and that there is a great concentration of energy in this path. In the case of the large surface lightning-arrester proposed no such condition can exist, as at the time of a heavy discharge there is a uniform path of high conductivity.

The other objection is the possibility of freezing the electrolyte. This objection, of course, would hold only in the case of high-voltage insulations where it would be necessary to put the arrester outside the station. The writer thinks that in case of this trouble with a three-phase installation of these arresters, it would be a comparatively simple matter to put the three sets of arresters either in a pit below the frost line or in a cabinet above the surface, according to drainage conditions. This would act to shield the arresters from wind and shaking. It is well known that a liquid if kept absolutely still will not freeze when brought to a temperature far below its freezing point. It would probably be found that the temperature would never get sufficiently low to cause freezing solid. Experiments show that it is only when the electrolyte is frozen solid that it ceases to have its peculiar resistance characteristics.

P. H. Thomas (by letter): Mr. Creighton speaks of the "discovery of the true non-arcing conditions of shunted gaps" which he distinguishes from "the unstable condition of a shunted arc" that "has been known for a long time", by considering the latter as a phenomenon having to do with alternating current whereas the former is really a shunted direct current operating for a part of a cycle. This distinction does not appear to me to be well founded. If we have a number of gaps shunted by a resistance, and pass a static discharge through these gaps while they are connected to a source of alternating potential, there will be of course current flow through the resistance and there will be a tendency for current to flow through the gaps following the static discharge. Whether a sensible current will appear in gaps depends, obviously, upon the voltage maintained across the gaps regardless of whether there may be resistance in shunt or not; whether the current continues in the shunted gaps or not depends also on this voltage and not directly upon presence, absence, or value of the shunt resistances. If the source of current is able to supply a smaller amount of current through the resistance than will maintain an arcing voltage upon the gaps, manifestly no current will follow the static discharge in the gaps. If, on the other hand, a sufficient current can be supplied by the source of electromotive force to maintain a sufficiently high voltage upon the gaps, current must inevitably follow the static spark therein. The shunt resisance has not a direct effect upon the arc in the gaps; it merely effects the potential of the terminals of the gap.

If now the static discharge occurs at one portion of an alternation, the voltage at that moment impressed upon the gaps will have one value; if at another part of an alternation, another value. There must be a portion of each alternation during which the generator voltage is so low as not to allow current to flow in the gaps following a discharge. On the other hand, if the current capacity of the source be sufficient there will be times within the alternation when the voltage impressed on the gaps will be sufficient to cause a following of current in the gaps. The most favorable condition for such following is obviously that the static shall occur approximately at the maximum of the waves. It appears from Figs. 3 and 4 of Mr. Creighton's paper that the static discharge which he times with a synchronous motor occurs early in the cycle, at an instance when the generator electromotive force is far from its maximum. This condition is manifestly an unfavorable one for the following of current in the gaps. If Mr. Creighton has always passed the static through the shunted gaps at this part of the cycle, it would not be safe to draw any inferences as to the non-arcing quality of the arrangement under the conditions of actual service where the discharge is sometimes likely to come at the maximum of the wave.

The arc suppressing power of the shunt resistance depends entirely upon the current that is to pass through this resistance following the static discharge. The shunted lightning-arresters heretofore used have exactly the same electrical arrangement as Mr. Creighton's. When the current tending to flow in the resistance after a discharge is small, or when the discharge occurs at a low-voltage point of the cycle, no current whatever will appear in the shunted gaps. When, however, more current flows through the resistance there will be some current flow in the gaps this current will cease at the first alternation if it be not too heavy, or so much current may be forced into the gaps that they will continue the arc. There is no difference between the apparatus of Mr. Creighton and the previously shunted gaps; he has simply subjected them to milder conditions.

I would call attention to the curious form of the current curves in Fig. 1, which I believe to be generally correct. The first time it is met with, the high voltage at low currents is quite a surprising feature.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, New York, April 15, 1907.

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THE ROWLAND TELEGRAPHIC SYSTEM

BY LOUIS M. POTTS

Since the invention of the Morse system more than fifty years ago, telegraphy has grown by law of natural evolution to meet the demands of an increasing business. The Morse system has been the measure of the potential of the telegraph wires and of the operator. To handle a continuously increasing business, telegraph managements have been compelled to stretch annually new copper wires and to employ new operators, because the present wire systems have been worked continuously to their capacity and operators to their highest efficiency under the conditions imposed by Morse methods. It is evident that this indefinite extension of wire systems and the force of operators involves the consequent investment of enormous capital and increases indefinitely annual maintenance charges.

In all other fields of modern industrialism when manual methods have thus shown themselves to have reached the limit of their development, and to be capable only of clumsy augmentation without radical resulting advantages, necessity has found the apparatus to meet the demand, and the introduction of machines and machine methods has inaugurated a new era of increased capacity and economy. For some years, telegraph managers have realized that the manual Morse system has about reached its limit of development and they recognize that further progress must result from the use of machine telegraph methods. They have understood that the machine to be valuable must despatch a greater volume of traffic on existing wires and give greater efficiency to the operator than can be done with the now highly developed Morse methods. The field of machine telegraphy thus determined has proved to be a most fascinating one to inventors and has enlisted the constant attention and efforts of a large number of able and ingenious men. As a consequence, various telegraphic devices and machines have been brought forward at different times to meet the demand of the situation, but since none has heretofore remained predominant in the field, it is clear that none has been able to meet the exacting requirements attending commercial operation.

The purpose of this paper is to describe a system of telegraphy which meets the requirements of the telegraphic service of today by providing for an enlarged wire capacity, combined with greater efficiency of the operator and adaptability to the requirements than any system previously described. In practical operation, it has continuously demonstrated its efficiency in despatching an enormous volume of business with regularity and accuracy on a single wire, while the operators employed have been not necessarily skilled in the use of the Morse code.

GENERAL DESCRIPTION

The Rowland Telegraphic System is a sytem in which the two features of multiplexing and printing are combined. The multiplex feature is accomplished by the synchronous operation of the instruments at the terminal stations. By this means, in an octoplex installation each of the four operators is given the use of a telegraph wire one-fourteenth of a second, at intervals recurring 3.5 times a second.* In addition, the wire is duplexed by the polar duplex method, so that four transmissions in each direction, or eight in all, are obtained. In a quadruplex installation, each of the two operators is given the use of the wire for one-seventh of a second at intervals recurring 3.5 times a second; and the duplexing of the wire provides for two transmissions in each direction, or four in all.

The printing is accomplished by a perfectly direct method; that is, no punched or otherwise prepared tape is used at either the sending or receiving station, but the printing is controlled directly from a keyboard, practically identical with that of a typewriter. The total duration of the operation, from the depression of the key at the sending station until the character is printed at the receiving station, is less than one-quarter of a second.

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*The normal operating speed is fixed at 210 revolutions of the line unit per minute, or three and one-half revolutions per second, or one revolution in one divided by three and one-half, or two-sevenths of a second. This interval of two-sevenths of a second being divided among four operators, gives each one the use of the wire for two sevenths divided by four, or one-fourteenth of a second.

All the operations at the receiving station are controlled from the keyboard at the sending station. This keyboard is identical with a typewriter keyboard, except for three additional keys, the so-called " lining," "backing," and "blanking" keys. The lining key is for the purpose of enabling the sending operator to move the paper from line to line on the printer at the distant station, the paper being moved the distance between two consecutive lines each time this key is depressed. The backing key is used for the purpose of returning the carriage at the distant station to the beginning of a new line. The blanking key is used for the purpose of shifting a telegraph blank on the printer at the distant station to the proper position for a new message. By the use of these keys in conjunction with the other keys, the operator has perfect control over the receiving printer at the distant station. All the operations performed on a typewriter, such as paragraphing, tabulating, etc., can be performed equally well with this keyboard.

At the sending station, in addition to the keyboard there is a home-recorder and a signal light for the guidance of the operator. The home-recorder consists of a tape-printing arrangement. A narrow paper band passes directly over the keyboard, and (directly) in front of the operator. On this tape is recorded the character corresponding to each key depressed. When the lining, backing, and blanking keys are depressed, in place of performing these operations on the home-recorder, characters are printed on the tape, indicating that these keys have been operated properly. When the backing key is depressed, an arrow is printed on the tape. This arrow, as the tape moves, travels with the tape along a properly graduated scale and indicates to the operator the position of the character last printed on the page printer at the receiving station.

In addition to the home-recorder, there is placed beside the keyboard a small red signal-lamp for the guidance of the sending operator. When the carriage at the receiving station has approached within a certain number of characters of the end of the line, this signal lamp automatically lights, thus performing the same function as the bell on the type-writer and preventing the sending operator from piling letters at the end of the line. When the operator depresses the backing key, this light goes out as soon as the carriage at the distant station has returned to the beginning of a new line.

At the receiving station the messages are automatically printed in page form on a long band about eight inches wide, (See Fig. 1 for facsimile of message) which may be prepared with the regular telegraph blank, or any other blank which may be desired. On these blanks the messages may be printed in any desired form, there being the same flexibility as can be obtained by the use of a typewriter. The page printer consists of a light carriage which carries the paper and is capable of being moved in a horizontal direction for purposes of spacing.

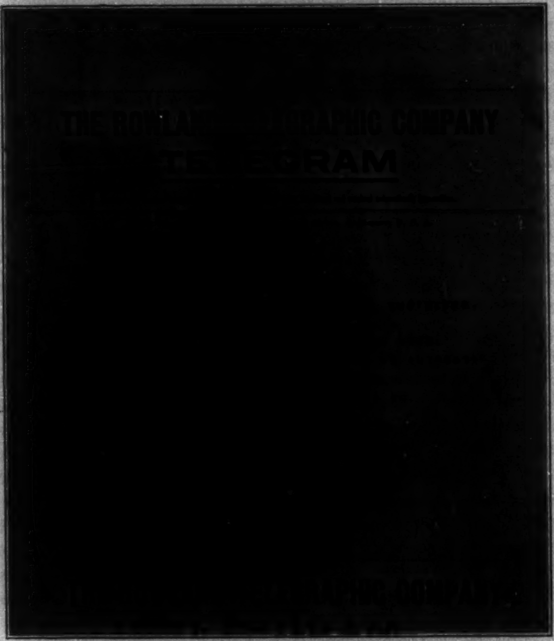

Fig. 1—Facsimile of Rowland Telegram

FIG. 2—Rowland Octoplex, sending side

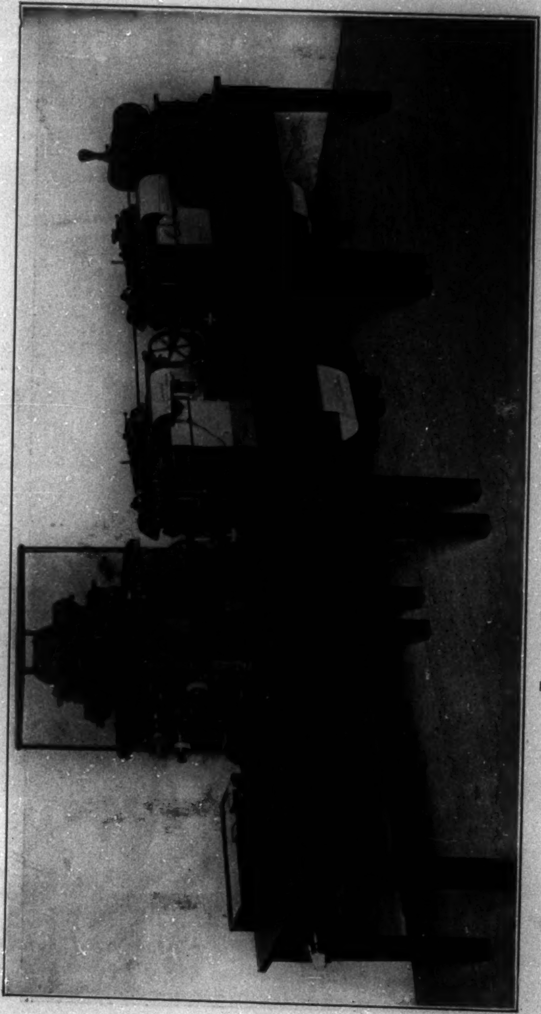

FIG. 3—Rowland Quadruplex, receiving side

The paper is carried around a roll, which by rotating places the paper in position for a new line. The paper is carried between a platen and a constantly rotating steel wheel, having the various characters engraved on its rim. When a character to be printed is directly over the platen, the platen throws the paper against the type-wheel, which is continually inked by a small felt ink-wheel. All the above motions and the operation of the platen are produced by electromagnets under the perfect control of the sending operator.

SPEED OF OPERATION

The speed of each operator is limited by the number of times per minute the keys are unlocked. The normal operating speed being 210 revolutions of the driving mechanism per minute, the keys are unlocked 3½ times each second, or 210 times per minute. One key can be depressed each time the keys are unlocked. The theoretical maximum speed is about 40 words per minute. On account of the time required for returning the carriage to the beginning of the line, and also because of the fact that the operator does not always take advantage of the unlocking of the keys, when operating for long periods, the speed in actual practice is about 35 words per minute. However, except on the longest lines the speed of the operation of the machine may be very materially augmented. Upon the basis of 30 words per message, which is generally accepted as a fair average, this speed is equivalent to a rate of about 75* messages per hour, per operator, or 300 in each direction per hour, per wire, or 600 per hour, per wire for the full octoplex.

TELEGRAPHIC CURRENT

In the Rowland system of telegraphy, the basis of the telegraphic current is an alternating current.

In an octoplex installation the current, at the normal speed of operation, has a period of 98 cycles per second. The same current is used for signalling and synchronizing. This alternating current is sent over the line continuously. The signals consist in reversing certain combinations of waves, as will be described later.

Fig. 4, Curve I, quadrant *C* is an oscillogram of a block of 14 of the half waves of the basic alternating current. The half waves are numbered from 1 to 56, after 56 another block begins with No. 1, and so on. This block of 56, which lasts two-sevenths of a second, is divided into four blocks each, *A*, *B*, *C*, and *D*, each of which is assigned to a different operator, making four transmissions each way if duplexed as mentioned. Each block recurs 3.5 times each second.

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*A rate of 71 messages per hour has been maintained in commercial practice for all-day operation. A rate of 50 to 60 messages per hour is maintained with ease.

For the purpose of sending the actual printing signals, only 11 impulses are used in each block. One of the remaining three in each block is used for operating the lamp signals between the stations, and one other, in the *D* block, is used for the letter finder impulse as is described later. The sending of a signal for the printing of a character at the distant end consists in the reversal of two of the 11 impulses. By variously combining two at a time of the 11 impulses, a sufficient number of signals is obtained for telegraphic purposes, that is, 55 possible different signals, 51 of which are actually used, any one of which may be transmitted during a time in which 11 impulses pass over the line.

Fig. 5 shows how the 11 half-waves are combined to obtain the 51 signals used.

Fig. 4, Curve 1, is an oscillogram of the current received and which vibrates the main-line relay. At the particular time of the oscillogram the *A* operator is transmitting the signal period (•) The *B* operator is transmitting the signal for lining and the *C* operator is transmitting no signal and the *D* operator is transmiting the letter *A*. The letter-finder wave is also shown reversed, as this is always reversed. The carriage on the *D* receiving printer is at the end of a line and the lamp signal in the *A* quadrant is reversed.

In a quadruplex installation the current has a period of just one-half that of the octoplex, or 49 per second; and the waves shown in the *C* and *D* blocks in Fig. 4 are omitted, the waves being numbered from 1 to 28 and after 28 the start being again made with No. 1. Each block recurs, as in the octoplex, 3.5 times a second and thus the time for each wave is twice as great as in the octoplex and the frequency is therefore one-half.

GENERATING THE ALTERNATING CURRENT

The alternating current used for the Rowland system is generated directly by the machine itself, this being necessary because the frequency of the current must correspond exactly with the speed of the machine. The current is generated by a dynamo or by a transformer and a commutator together with

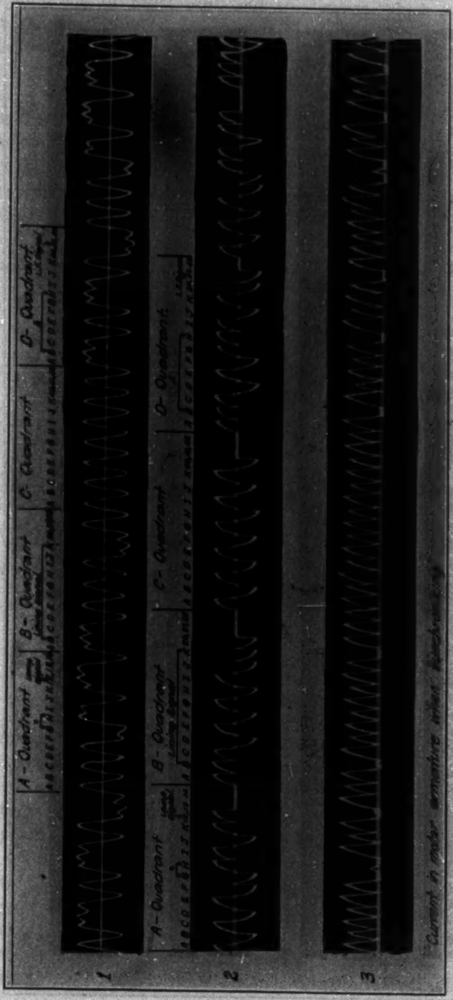

FIG. 4, Part I—Oscillogram

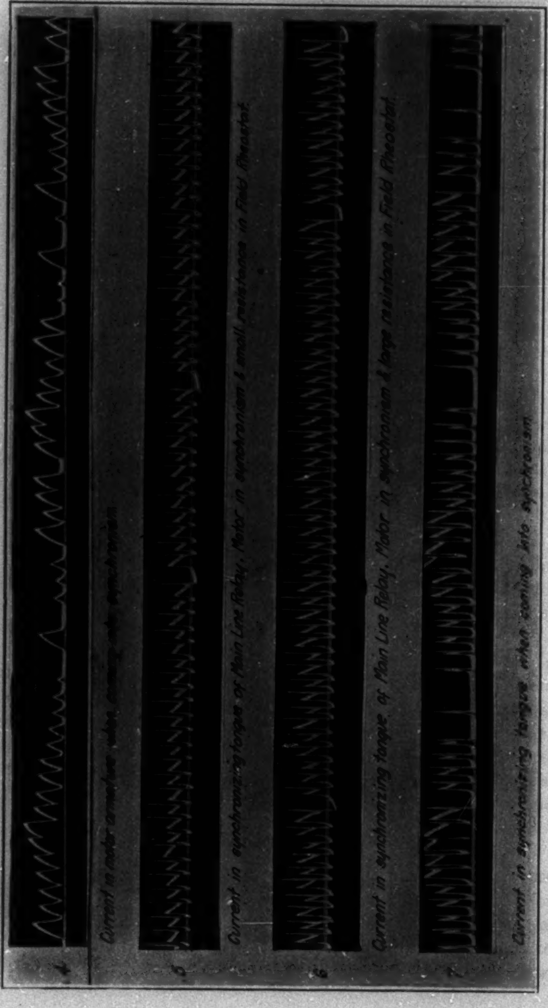

FIG. 4, Part II—Oscillogram

Curves 5, 6, and 7 above are printed in the reverse direction to that of the previous curves, and the lapse of time is from right to left, in place of left to right.

a combination of resistances and condensers which serve no other purpose than to reduce sparking on the commutator.

The transformer consists of two primary and two secondary coils with an iron core. The commutator used in connection with the current generator has eight rings, one being a solid collecting ring and the other seven being crown sections having in the octoplex 56 segments and in the quadruplex 28 segments every alternate segment being electrically connected.

One terminal of each of the two primary coils of the transformer is connected directly to negative. The other terminals

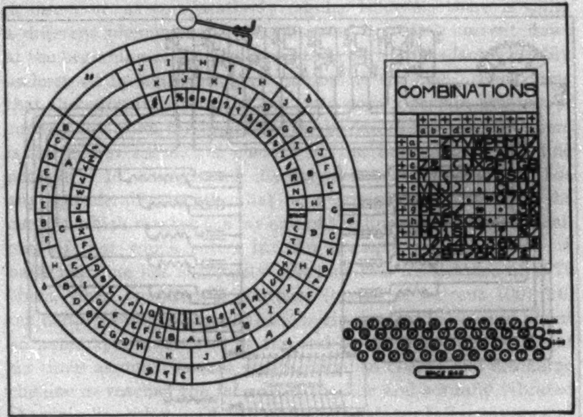

FIG. 5—Combination diagram

are connected to the alternate segments of the first crown section, the coils being so connected that the current flows through them in such a manner as to magnetize the iron in opposite directions. The theory of the operation of this current generating apparatus should first be considered with regard only to the solid collecting ring and the first crown section (see Fig. 6), the other crown sections simply serving the purpose of stopping the spark and preventing wear of the commutator and brushes. By taking into consideration only these parts, it will be seen that the brushes (which are all in metallic connection) alternately connect the two open terminals of the two primary transformer coils to the positive of the direct-current voltage, thus continually reversing the magnetism of the iron core of the transformer as the brushes pass from one segment to the next. These reversals of the magnetism of the iron core induce in the secondaries of the transformer an alternating current, the further operation of which will be explained later.

The remaining six crown sections of the commutator have their alternate sections connected to the two primaries in a similar manner to the first crown section, except that in place of being connected directly they are connected through resistances shunting condensers, these resistances increasing in value from the second crown section to the last. The brushes are so arranged on the trailer arm that the brushes leave corresponding segments of different rings in the order of increasing resistance. By this arrangement the spark which would otherwise occur when the brush leaves the segments is prevented.

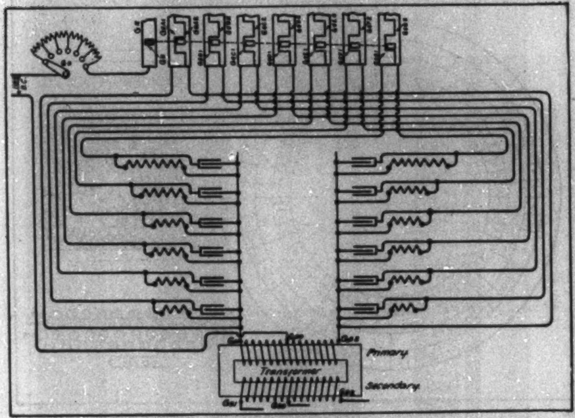

FIG. 6—Current generating connections

On the end of the brush arm opposite to that carrying the contact brushes are mounted two carriers, the first one of which carries a piece of dry felt, the second one a piece of felt slightly oiled. These two carriers are operated by springs so that the felt is pressed against the surface of the commutator in such a way that the dry piece of felt cleans the commutator while the second piece of felt furnishes the commutator with fresh lubricant. The action of these pieces of felt is to diminish the spark on the commutator and also to prevent mechanical wear on both the brushes and commutator.

AMOUNT OF CURRENT REQUIRED

In the Morse system of telegraphy, and in fact in most systems of telegraphy, it is customary to measure the currrent by applying direct voltage to the line so that the same amount of current flows at both stations. When the signalling current is reversed in direction at comparatively regular intervals there is quite a different phenomenon. In this case a greater current flows at the beginning of the line than at the end. This fact is readily understood by considering the action of the line. Each time that the current is reversed not only does a certain amount of current flow from the beginning to the end of the line, but there is also a large amount of current at the beginning of the line necessary to charge and discharge it. When the line has any considerable length, that is, a considerable capacity, the current which reaches the far end of the line will be only a small part of that which enters it. An example will illustrate: A particular line has a capacity of 8.4 mf. and a resistance of 2070 ohms, when operated in octoplex (period of current 100) 240 milliamperes were sent out at the beginning of the line and about 35 milliamperes received at the end of the line; that is, about six times as much current was required to charge and discharge the line as reached the far end of the line and actually vibrated the main-line relay. Of course, a similar state of affairs is present when a line is operated by any reverse-current system, such as the Morse duplex or quadruplex; but the phenomenon is not often observed as the steady state of the current is measured and alternating-current measuring instruments are not ordinarily required in a telegraph office.

For the proper operation of the relays used with the Rowland system, it is necessary to have at least 25 milliamperes at the receiving station. A very good practical working value for this relay is about 35 milliamperes, and when line conditions are very bad it may be found necessary to use 45 milliamperes. These values of current are required, not because the apparatus will not operate with less, but the signalling current must be sufficiently large to overbalance the effect of leakage and induction currents.

DUPLEXING

The duplex feature of the Rowland system is obtained as in many other systems of telegraphy by the use of a differentially wound relay and an artificial line, which represents as nearly as possible the real line as regards its resistance and capacity.

In order that the main-line relay may not be affected by the outgoing current, it is necessary that the currents in the two sides of the relay should be identical. In order that one may know when such is the case, a large resistance (about 5,000 ohms) is connected from one side of the relay to the other. Across a small part of this resistance (about 50 ohms) a telephone is connected.* When the currents flowing through the two sides of the relay are identical, no current will flow through this shunt and consequently there will be no sound in the telephone. By means of plugs it is possible readily to change the resistance of the artificial line, and also to move the condensers to any part of this resistance and thus to adjust the currents in the two sides of the relay until they are equal in phase and value. In the Rowland system the alternating characteristic of the current causes the balance to depend more directly on the capacity of the line than on its resistance. The balance used in its operation, therefore, is much more stable under varying conditions of the weather than in such a system as the Morse quadruplex, in which the resistance must be kept adjusted to the varying conditions, since the weather has much greater effect on the equivalent resistance of the line than on its capacity.

SYNCHRONISM

In most of the systems of multiplex telegraphy that have ever been tried the principle of synchronism has been used; that is, the apparatus at either end of the line has been operated in unison with that at the other end. In most synchronous systems of telegraphy, synchronism is obtained by adjusting the apparatus at each station so that it rotates very closely to some predetermined speed and in some way, at definite intervals, a correcting impulse is sent over the line; by this means the position of the apparatus is changed by the amount it has deviated from the other machine since the last correction. All methods of synchronism based on this principle have proved that they require extremely delicate adjustment, and even under the best conditions are subject to frequent disturbances.

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* Recently a double-needle indicating instrument has been devised for use in connection with the Rowland system; one needle indicates when the resistance referred to has been properly adjusted, and the two needles by both giving zero readings indicate when the capacity has been adjusted and located.

The synchronism as used in the Rowland system of telegraphy is of a continuous and stable character. The synchronism is maintained by the use of every impulse which comes over the line, (of which there are in the octoplex 196 per second) and not a small fraction of the total number, as in the case of the systems referred to above. These impulses come at such a rapid rate that on account of the large inertia of the moving parts no effect is observed due to each impulse separately; but the regulation is entirely due to the integral effect of a large number of impulses, so that any variation of even a comparatively large number of the impulses will produce no sudden disturbance of the synchronism.

POTTS' SYNCHRONIZER

This synchronizer (which is the form now used on the Rowland machines) consists of a small direct-current shunt motor, (See Fig. 7). On a shaft driven by this motor is mounted a trailer Z_b which passes over a crown commutator having alternate segments electrically connected. This crown commutator has such a number of segments that each segment corresponds to a half wave of the alternating current used for signalling. It will be seen that the effect of this brush arm and commutator is identical with that of the vibrating tongue of a relay. The alternate segments of this crown commutator are connected to the two contacts of the synchronizing end of the main-line relay. In series with the armature of the motor above referred to is a resistance Z_r. One side of this resistance is connected to the synchronizing tongue M_{st} of the main-line relay. The other terminal of this resistance is connected to the trailer Z_b.

The tongue of the main-line relay is kept in continuous vibration by the alternating current from the distant station, and the trailer Z_b is kept in continuous rotation by the motor. If the tongue of the relay is on the side contact which is connected to the set of segments of the crown commutator which the trailer is touching at the same time, it will be seen that the resistance Z_r is short-circuited; while if the tongue of the main line relay is on the side contact of the relay which is not connected to the set of segments of the crown commutator which the brush Z_b is touching at the same time, the resistance Z_r will be in series with the armature of the motor. In one case the armature will receive a much greater current than in the other.

Consider, first, the case when the vibrations of the tongue of the main line relay and the rotation of the brush arm bear such a relation to one another, that as long as the tongue M_{st} is against the contact M_{sc_1} the brush Z_b is in contact with the segments Z_{s_1}. If this condition is maintained it will be seen that the resistance Z_r is continuously shunted.

Secondly, consider the case when the vibrations of the tongue of the main line relay bear such a relation to the rotation of the brush arm, that when the tongue M_{st} is on the contact M_{sc_1} the brush is on segments Z_{s_2} and when the tongue is on the contact M_{sc_2} the brush is on the segments Z_{s_1}. If this condition is continuously maintained it will be seen that the resistance Z_r is continuously in circuit with the armature.

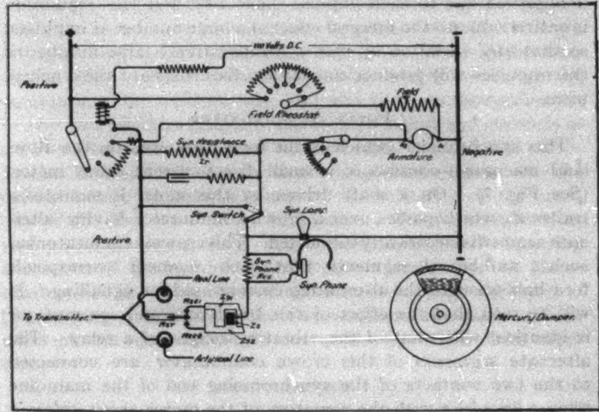

+
110 Volts D.C.
−
Positive
Field
Field Rheostat
Syn. Resistance
Zr
A
A
Armature
Negative
Syn. Switch
Syn. Lamp
Positive
Syn. Phone Res.
Syn. Phone
Real Line
Msc1
Zs1
To Transmitter
Mst
Zb
Msc2
Zs2
Artificial Line
−
Mercury Damper

FIG. 7—Synchronizing connections

Thirdly, consider any case in which the vibrations of the relay tongue and rotation of the brush arm have some relation between the above two. If any relation between the first two mentioned is continuously maintained, it will be readily seen that at rapidly recurring intervals the resistance Z_r will be in circuit and out of circuit. Depending upon the relation between the vibration of the tongue and the rotation of the brush arm, the intervals during which the resistance is in circuit and out of circuit will vary in length; and in addition to the regular current flowing through the armature, there will be a pulsating current flowing through the same and the strength of these impulses will depend upon the relation existing between the vibrations of the tongue and the rotation of the brush arm. Consequently, while the relay tongue is vibrating in unison with the rotation of the brush arm, there can be various amounts of current flowing through the armature of the motor, depending upon the relation of the relay tongue and the brush arm. (This relation is spoken of as the phase difference).

Let us assume that the relay tongue and the brush arm have such a relation that the current allowed to flow through the armature is of the correct value to maintain the speed of the motor at the same value continuously. If the rate of vibration of the relay tongue increases, the relation between the vibration of the relay tongue and the rotation of the brush arm will change, but in such a manner as to strengthen the impulses flowing through the armature; and consequently the speed of the motor will be increased, but only until this speed corresponds to the rate of vibration of the tongue. If the armature of the motor attempts to go faster than the vibrations of the relay tongue, the impulses through the armature are weakened and the speed is kept normal. If the motor attemps to go slower the impulses are strengthened and the speed of the motor is still kept normal. Consequently the speed of the motor follows any changes in the vibrations of the tongue and any tendency for the motor to change its speed, as, for instance, a change in the voltage in the power circuit, is immediately compensated for by a slight shift in the phase difference above mentioned. In starting the machine, synchronism is obtained by the use of a rheostat in series with the motor field.

The operation of the synchronizing device will be better understood by referring to Fig. 4 which gives several oscillograms of the synchronizing current under different conditions. Curve No. 3 is the current through the motor armature when in synchronism, and Curve No. 4 is same when the motor is coming into synchronism. Curve No. 5 shows the current furnished to the motor by way of the vibrating relay and not the total current in the armature of the motor and for a high value of current in the field of the motor. Curve No. 6 is the same as No. 5

except that a much smaller value of current is flowing in the fields of the motor. In both Curve No. 5 and No. 6 the motor was in synchronism. The difference in length and value of the impulses in the two cases is to be noted. Curve No. 7 shows the same current as No. 5 except for the condition when the motor is coming into synchronism. The rheostat is regulated until synchronism is obtained.

If the above arrangement is used alone, it will be found that the synchronism will not be steady, but will oscillate; that is at rapid intervals the speed of the motor will increase and decrease between certain limits. These oscillations are prevented by mounting on the high-speed shaft of the motor a so-called viscous damper. In one form this damper consists of a steel fly-wheel having a hollow rim which is nearly filled with mercury. The friction between the rotating mercury and the rotating rim of the fly wheel rapidly dampens any vibrations which tend to take place and makes the synchronism almost, if not quite, dead-beat. This effect of the mercury damper is identical with the effect produced on the vibrations of a pendulum by immersing it in molasses or mercury.

In regard to the practical operation of the above method of synchronism, it may be stated that the synchronism is often maintained for a whole day continuously without a single failure. Line swings of short duration do not cause it to loosen the letter, but cause an oscillation for an instant. All the variations of voltage, etc., under commercial conditions are automatically taken care of. To illustrate, in a test of this point changes in the conditions, which would cause the motor to change its speeds 50% if the synchronizing device were cut out, have been made without loss of synchronism.

Synchronous Indicator

In addition to being able to produce synchronism, it is necessary to have some means of knowing when synchronism has been obtained. There are many methods of doing this. Two methods are usually provided.

First. The synchronizing telephone.

This is a telephone in parallel with a small resistance, through which flows a small part of the pulsating current which flows through the armature of the motor. If synchronism has not been obtained, sounds of two different pitches will be heard in the telephone. If the speed is sufficiently near synchronism beats will be heard, similar to those produced when two keys of nearly the same pitch on an organ are sounded at the same time. As the speed more nearly approaches synchronism these beats will follow each other at greater intervals; and finally, when synchronism has been obtained, there will be a smooth sound of a definite pitch.

Second. The synchronizing lamp.

An incandescent lamp is connected so that it receives a pulsating current similar to that passing through the armature of the motor and the telephone. When synchronism has not been obtained the light of the lamp will pulsate; when synchronism has been obtained the light of the lamp will be steady.

FINDING THE LETTER

It will be noted from the description of the synchronizer that every alternate segment of the synchronizing commutator is in electrical connection, and that consequently when synchronism is obtained the brushes may be on any one of 28 segments in the octoplex, or on any one of 14 segments in the quadruplex. Before the signals can be received properly, it is necessary that the trailers of the sending and receiving stations shall be on corresponding segments.

The operation of shifting the brushes so that they are on corresponding segments is the so-called "finding the letter." For this purpose, at the sending station the impulse corresponding to the fifty-fifth segment (in the quadruplex it is the twenty-seventh [segement) is reversed every revolution. At the receiving station the fifty-fifth segment in the octoplex, or the twenty-seventh in the quadruplex, operates the "letter finder" relay, identical in connections with a selecting relay. This relay is so connected, that when it receives a normal unreversed impulse it is against its rear contact; but when it receives a reversed impulse it is against its front contact.

A gear driven by the motor pinion on the line unit, at a speed of 3.5 revolutions per second—the normal operating speed—carries a pawl which engages with a 28 toothed ratchet; in the quadruplex the ratchet has 14 teeth. This ratchet is fixed rigidly on the gear which drives the commutator brushes. The motor pinion, then, drives the gear carrying the pawl, and the pawl engaging the ratchet drives the train of gears carrying the brushes on the commutator. An electromagnet attached to the frame of the machine operates a plunger which causes a pin to trip the pawl on the ratchet, dropping it back one tooth each time the magnet is operated. The circuit of the magnet is completed through a resistance, a push button, and the back contact of the letter finder relay.

If synchronism has been obtained and the brushes are not on corresponding segments at the sending and receiving stations, the letter finder relay will be back, and when the push button is depressed the letter finder magnet will operate and the pawl will drop back one tooth in the ratchet each revolution until the brushes are on corresponding segments, when the reversed fifty-fifth impulse will fall on the letter finder relay, and the circuit of the letter finder magnet will be broken. An incandescent lamp is connected from the positive terminal through the back contact and tongue of the letter finder relay to negative. As long as the brushes are not on corresponding segments this lamp will be lighted. When the brushes are on corresponding segments, and the relay tongue is therefore on its front contact, the lamp will go out indicating that the letter has been found.

TRANSMISSION OF THE SIGNALS

The transmitting apparatus proper consists of a keyboard, a sending commutator, and a transmitting relay. (See Fig. 8.) The keyboard consists of a number of levers, one for each character, pivoted in the middle and each carrying a heavy contact strip which, when the key is depressed, makes contact with two pins. On one end of this lever is a small lip S_2 which engages a steel bar S_1, passing above the keys. By means of a cam S_4 and a lever S_3 this bar is given a reciprocating motion. In one position it permits the keys to be depressed at will, and in the other position it holds the keys down or up, as the case may be. At the usual speed of operation this bar is made to oscillate three and one-half times per second.

The sending commutator consists of a ring dvided into 56 segments in the octoplex, or 28 in the quadruplex. Each of these segments corresponds to a half-wave. Eleven segments being connected to each keyboard, each key when depressed connects two of these segments to the negative.

The transmitting relay consists of a polar relay of ordinary form, one coil of which is connected through a high resistance in such a way as to receive current continuously, giving the transmitter tongue a bias which holds it normally against one contact. The other coil when energized by current through the sending commutator, keyboard contact pins and key lever, and a resistance, attracts the transmitter tongue to the other contact. This disconnects the line from one secondary of the transformer and connects it to the other, thus sending an impulse the reverse of the normal. When the brush passes over such segments as are made negative by a depressed key on the keyboard, the magnet S_M is energized, and the impulses corresponding to these segments are reversed. The cam S_4 is so geared to the brush S_6 that the keys are always locked when the brushes pass over the segments corresponding to that particular keyboard.

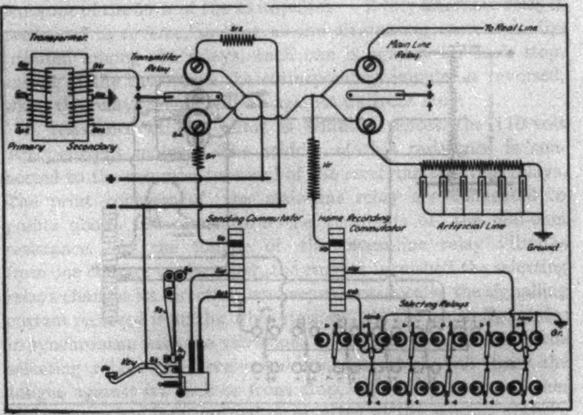

Transformer
Transmitter Relay
To Real Line
Main Line Relay
Primary
Secondary
Sending Commutator
Home Recording Commutator
Artificial Line
Ground
Selecting Relays
Gr.
Key

FIG. 8—Transmitting and home-recording connections

HOME RECORDER

In addition to printing the message at the distant station, a record is also obtained at the sending station for the guidance of the operator and for record purposes. This record is produced by the outgoing signals, in a manner similar to that used at the receiving station. For this purpose each sending position is supplied with a bank of home-recording selecting relays identical with those supplied at the receiving position. These relays, instead of being operated by a current from the contacts of the main-line relay, are operated by a current shunted off from the main signalling current just before it enters the main-line relay. This signalling current is distributed to the various home-recording selecting relays by a commutator of 56 segments (or of 28 segments in the quadruplex) identical in construction with the receiving commutator.

The home-recording printer, in the present form, is a tape printer. The operation of this tape printer is perfectly identical with that of the page printer, except that the mechanism for lining, blanking, and backing is omitted. (See description of page printer). Corresponding to the back contact signal on the page printer at the distant end, there is placed on the sending tape printer a small incandescent lamp which lights whenever the receiving lamp relay is against its front contact; that is, whenever the carriage on the page printer is within a certain number of letters of the end of a line, notifying the sending operator of this fact.

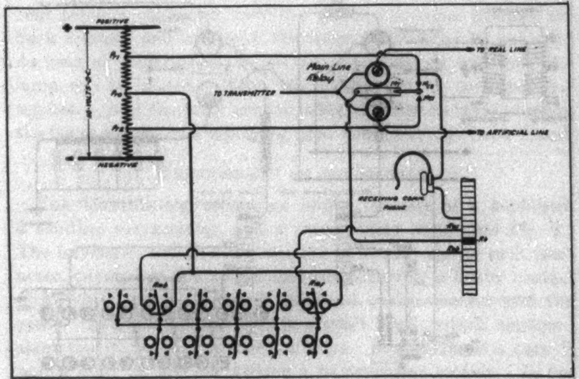


FIG. 9—Receiving connections

RECEIVING THE SIGNALS

On account of the fact that the signals are produced by a combination of two out of eleven, it is necessary that the first of the two signals received be stored up in some way until the second signal is received, before the corresponding character can be printed. This is accomplished by the use of polarized relays, one corresponding to each of the eleven impulses. Each printer is furnished with a bank of 11 receiving selecting relays. (See Fig. 9.) For receiving the signals there is employed a vibrating tongue of the same line relay which is used for synchronizing, the relay having two independent tongues and pairs of contacts, one for synchronizing and one for printing.

The receiving, like the sending commutator, consists of a ring divided into 56 segments in the octoplex, or 28 segments in the quadruplex, one segment corresponding to each of the 56 or 28 impulses. One terminal of the winding of each relay is connected to a common point, and the other terminal to the corresponding segment of the receiving commutator, so that each relay represents one of the 56 or of the 28 impulses. Every alternate relay is connected in reverse, so that as the alternating current is distributed among the relays, each one is against its back stop, except in the case when the corresponding impulse is reversed, when the relay tongue will be against its front stop.

A resistance of 600 ohms is shunted across the 110-volt direct-current mains. The middle of this resistance is connected to the common terminal of the receiving selecting relays. The print contacts of the main-line relay are connected to points about 100 ohms from the terminals of the 600-ohm resistance. As the tongue of the main-line relay vibrates from one contact to the other, the current furnished the selecting relays changes its direction, and reproduces locally the signalling current received from the other station. As the brush R_b rotates in synchronism with the vibrations of the tongue M_T, each of the selecting relays will receive an impulse which will draw the tongue against its back or front stop, depending upon whether the impulse has been normal or reversed at the sending station.

Fig. 4, Curve 2, shows the impulses flowing through the selecting relays. The impulses shown correspond to those for the received current shown in Curve 1.

A telephone will be noted on Fig. 9. This is for the purpose of indicating the proper adjustment of the receiving commutator. When the commutator is not properly adjusted it is indicated by a loud rap in the telephone.

AUTOMATIC TRANSLATION OF RECEIVED SIGNALS INTO PRINTED CHARACTERS

The page printer, by means of which 51 different operations may be performed from the keyboard controlled by the operator at the distant station, involves the following features:

First. A solid steel type-wheel about 2.5 inches in diameter, on the circumference of which the characters to be printed are engraved. This type-wheel revolves continuously at the end of a horizontal shaft, and in synchronism with the trailers on the various commutators.

Second. A light paper carriage, carrying the paper which is fed from a roll underneath the type-wheel when new lines are to be made.

Third. A device to thrust the paper forward to make a new line.

Fourth. A device to move the paper carriage sideways to produce the space between letters and between words.

Fifth. A device to return the carriage to the beginning of a new line.

Sixth. A small printing magnet, which operates a hammer or platen which throws the paper against the lower side of the rim of the type-wheel, at the moment when the character to be printed has turned to its proper position above the line.

Seventh. A set of five polarized relays called the distributing relays, connected to the page printer by a cable, which serves the purpose of making contacts at proper moments for sending current to the print magnet to print; to a lining magnet to line; to a spacing magnet to move the paper sideways; to a backing magnet, which allows the carriage to return for the beginning of a new line; and to a blanking mechanism which rapidly feeds out the paper until a new blank is in the proper position for the beginning of a new message. Each of these operations is completely controlled by a key on the keyboard at the distant station.

Eighth. A combination commutator, the function of which will appear from the following description. Fig 10 shows such a commutator developed. This commutator consists of three rings being divided into a number of segments, one fifty-sixth of a circumference corresponding to each operation. The rings 1 and 2 are divided into various segments lettered from A to K. The arrangement of these segments are so chosen that at one point, and only one point, any two segments corresponding to a given character will be in line. The third ring is divided into various segments, and according as the combination at any particular point of the commutator is to print, space, etc., this segment of the third ring is connected to the corresponding distributing relay. All of the segments in rings 1 and 2 bearing the same letter are connected to the contact of the corresponding receiving selecting relay, in the bank of eleven selecting relays belonging to that page printer.

The operation of the page-printer will be readily understood by reference to Fig. 10, where the connections of the page-printer are shown. The incoming signal, which consists of two reversed waves, is first received, as elsewhere described, by throwing forward the tongue of the two corresponding selecting relays against their front contacts. By so doing, the segments of the combination commutator having the same letters as these relays will be connected to the frame of the bank of selecting relays, since the eleven tongues of this bank of relays are electrically connected to the frame. The brush bearing on ring No. 2 of the combination commutator is connected directly to negative, the frame of the machine, while the brushes on rings No. 1 and No. 3 are insulated from the frame, but connected to each other.

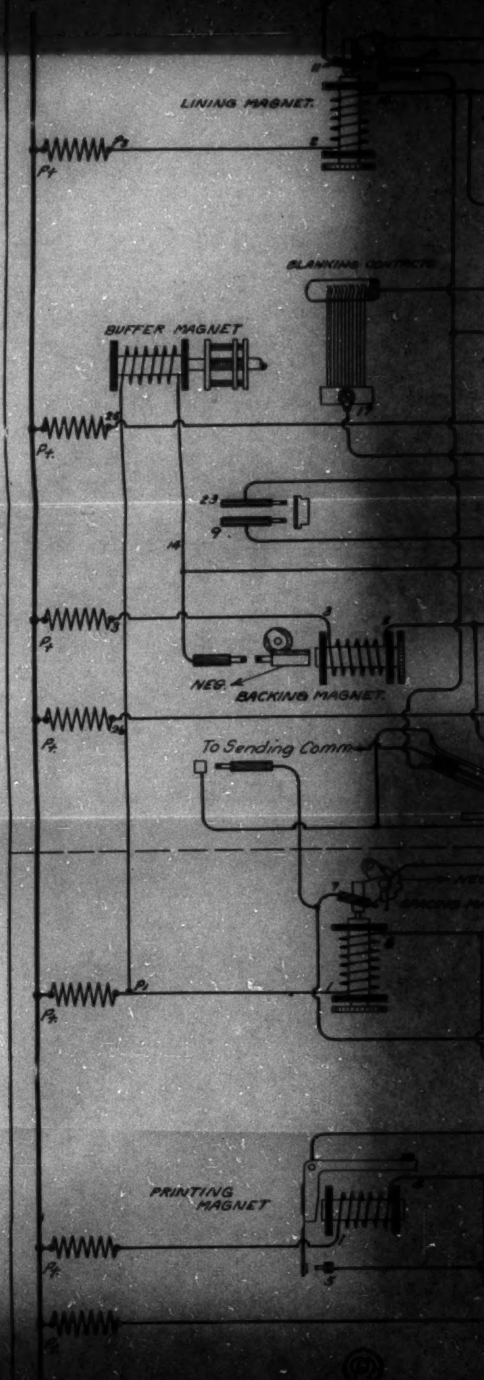
When the trailer brushes on the combination commutator, being in continuous rotation on the three rings Nos. 1, 2, and 3, rest at the same time upon segments of the commutator which are connected together, through the contacts and tongues of the two selecting relays which are against their front stops, an impulse will be sent through the wire *P* 12 and the front spool of the print relay. This will throw the tongue of the print relay forward and close the circuit of the print magnet, operating the hammer and throwing the paper against the type-wheel at the proper time to print the letter corresponding to the signal sent.

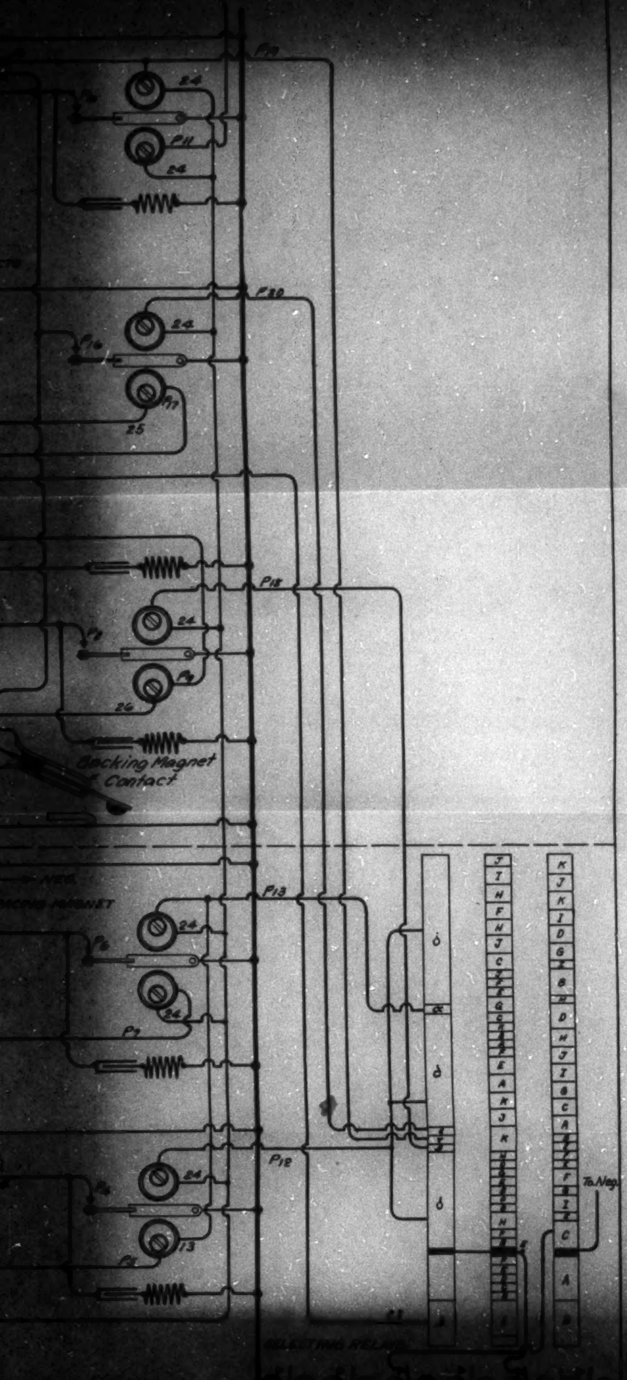
When the print magnet operates, a contact on the hammer will ground the contact 5, and thus send a current through the back spool 13, of the print relay, and also through the front spool of the space relay. This will open the circuit of the print magnet, thus releasing it, and at the same time will close the circuit of the space magnet. When the space magnet has operated the spacing mechanism of the printer, a contact attached to this mechanism connects the contact 7 to the negative, thus sending an impulse through the back spool *P* 7 of the space relay, and pulling the tongue of the space relay against its back contact, thus opening the circuit of the space magnet.

The electrical operation of the backing mechanism is similar to that of the printing and the spacing, except that the operation of the release contact is somewhat different. In order to throw the backing relay against its back stop, it is necessary to make two contacts. One of these contacts, 9, is made when the paper carriage has returned to the beginning of a new line, so that current continues to flow through the back magnet until the carriage is returned to the beginning of a new line. The other contact, through wire, No. 23, is made by the trailer brush passing over a short segment on the combination commutator. The " buffer " magnet is energized by current through wire No. 14 and a contact on the plunger of the backing magnet, as soon as the backing magnet is operated. When the carriage returns to the beginning of a line it is held by the buffer magnet, which prevents the carriage rebounding, until, at the next revolution of the trailers, contact is made on the short segment of the commutator, and current through wire No 23 and contact No. 9 and the back spool of the backing relay opens this relay and releases the backing and the buffer magnets.

The electrical operation of the lining mechanism is identical with that of the printing and the spacing. When the operator has finished a telegraphic message and desires to start a new one, the blank key is depressed. This throws forward the blanking relay against its front contact. This connects the front spool of the lining relay to negative by way of contact 16 and the blanking relay. The contact of the lining mechanism normally rests against the contact 16, and if the blanking relay is front the lining relay will be thrown front, and the lining magnet will operate and in so doing will ground the back spool of the lining relay through the contact 11, thus opening the circuit of the lining magnet, which will allow the negative contact of the lining mechanism again to throw front the lining relay. This process will continue and the paper will be fed out as long as the blanking relay remains forward. However, at definite intervals the paper is perforated, and as soon as the blank has advanced to the proper position the holes allow the brushes 17 to make contact through the paper with a negative connection on the frame. This sends an impulse through the back spool of the blanking relay, thus pulling the tongue of the blanking relay against its back contact and thus stopping the operation of the lining mechanism.

When the carriage is within a certain number of characters of the end of the line, a contact is made by the action of a strip on the carriage frame, thus grounding the segment on the sending commutator which corresponds to the back signal. This continues to send the backing signal to the operator at the distant


LINING MAGNET.
P1
P+
BLANKING CONTACTS
BUFFER MAGNET
25
P+.
23
9.
14
3
P+
NEG.
BACKING MAGNET.
26
P+.
To Sending Comm
7
6
1
P1
P+.
PRINTING MAGNET
1
5
P+
P+.


P19
24
P11
24
P20
24
P16
P17
25
P18
24
P8
P9
26
Backing Magnet
& Contact
NEG.
P13
24
P6
24
P7
P12
24
P4
P5
13
To Neg.
SELECTING RELAY
J
I
H
F
H
J
C
G
E
A
K
J
K
H
K
J
K
I
D
G
B
D
H
J
I
B
C
A
F
I
C
A

end as long as the carriage is within a certain distance of the end of the line. This is also so arranged that when the blanking relay is front and the paper is feeding out, it sends the signal to light the red lamp at the sending station, thus insuring that the sending operator does not begin a new message before the paper has stopped moving.

MECHANISM FOR PRODUCING THE UNISON OF LOCAL APPARATUS

In order that the motor which is synchronized by the impulses over the line, and which drives the brushes on the commutators directly concerned with the sending and the reception of signals, have as little and as constant an amount of work to do as possible, the printers and home-recorders are sometimes (particularly in large installations) driven by a separate motor, Fig. 13, which is kept in unison with the motor on the line unit. It is not only necessary that these two pieces of apparatus be kept in synchronism, but also that their commutators bear a definite relation to one another. In order that this may be the case, the mechanism which maintains the unison of these two pieces of apparatus is so arranged that this unison is possible only when the commutators bear a correct relation, the one to the other.

On the line unit is a commutator, known as the multiple-unison commutator, divided into twelve segments; and on the unison unit, which is the driving mechanism of the local printers, is a similar commutator of 12 segments, known as the unison unit commutator. The corresponding segments on these two commutators are electrically connected. The brush on the multiple-unison commutator is connected to negative. The brush on the unison-unit commutator is connected—after the unison-unit motor is brought up to speed by means of the starting box—to one terminal of the motor armature, and also to one terminal of the synchronizing resistance. The other terminal of the synchronizing resistance is connected to negative; and the other terminal of the motor armature to positive. The brushes on the unison-unit commutator are driven by the unison-unit motor.

When the line-unit and unison-unit motors are running at the proper speed the brushes on each commutator will be making 210 revolutions per minute. If the brushes are on corresponding segments of the two commutators, the synchronizing resistance will be short-circuited, and the armature of the unison-unit motor will be directly across the power mains. If the brushes are not on corresponding segments of the two commutators, the synchronizing resistance will be inserted in the armature circuit, reducing the speed of the unison-unit motor, which will run slowly until it has dropped back to a point where the brushes are again on corresponding segments on the two commutators, when the armature will again receive its full current. By adjusting the resistance in series with the shunt field of the motors, the speed can be regulated to such a point that the action of the brushes on the commutators, in short circuiting the synchronizing resistance, will keep the unison-unit motor in synchronism with the line-unit motor. It is of course not necessary to adjust this resistance every time the motor is started. This resistance is set for any speed of operation once for all, and the motor is then started just the same as any motor; *i.e.* by the use of a starting lever. The synchronism takes care of itself.

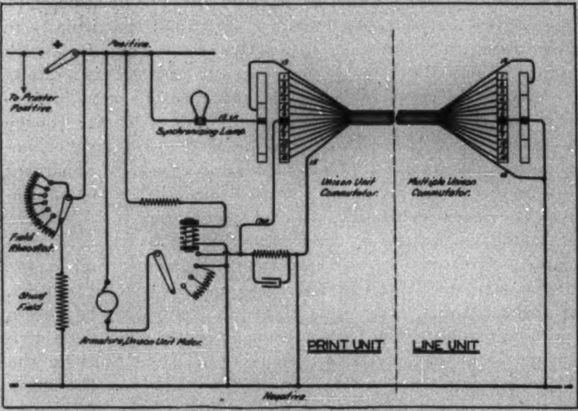

+
Positive
To Printer Positive
Synchronizing Lamp
Field Rheostat
Shunt Field
Armature, Unison Unit Motor
Unison Unit Commutator
Multiple Unison Commutator
PRINT UNIT
LINE UNIT
−
Negative

FIG. 11—Unison-unit connections

For the purpose of indicating when the two pieces of apparatus are in unison, a unison lamp is provided. The circuit of this lamp is completed through extra rings on each commutator. It will be noted by reference to Fig. 13, that this lamp receives no current when the two brushes are rotating in synchronism; but if the synchronism moves the distance of more than one segment, this lamp will receive an intermittent current and will thus indicate that the two pieces of apparatus are not in unison.

To secure a uniform rotation of the print-unit driving shafts, a mercury damper similar in action to that on the line-unit motor, is provided for the unison-unit motor. To assist further in obtaining as nearly as possible an absolutely uniform rotation of the type-wheel on the individual printers, so that the type-wheel will travel at all points in its revolution a fixed, definite distance between the time when the impulse is received by the print relay and the time when the platen strikes the paper against the type-wheel, and thus give uniform spacing between the letters, each type-wheel shaft is provided with a fly-wheel; and the driving dog on the end of the shaft, through which the motion is transmitted to the shaft, is made up by winding a flat steel spring into a spiral, one end of which is fastened rigidly to the shaft, and the other end of which engages the driving dog. The spring has a strip of heavy, non-elastic material wound with it, the action of which prevents rapid oscillations of the spring.

Method of Construction of Apparatus

The Rowland apparatus is divided into a number of units for convenience of manufacture and operation. Any unit can be quickly removed and replaced by another unit. In general any machine is divided into three units, the line unit, the correspondence unit, and the unison-unit. (See Figs. 2, 3, 12, and 13.) The line unit comprises the current generator, sending, receiving, and home-recording commutators, synchronizing device, transmitter and main-line relay and all the parts directly concerned with the line, in other words the purely telegraphic parts of the apparatus. The correspondence unit comprises the keyboard, home recording printer, and receiving printer; in other words, a duplex electrical type-writer. The unison unit simply serves to supply power to operate the correspondence units; it may be dispensed with in case of small installations, as they can be operated directly by the line, or a separate one may be provided for each correspondence unit if so desired.

Conclusion

From the foregoing discussion of the telegraphic situation and the description of the Rowland system, it has probably been understood already that the latter is constructed essentially to meet the demands of the former. A brief examination of the adaptability of the machine to the situation, however, is necessary in order to appreciate thoroughly its practical utility and efficiency.

The most important practical requirements of the telegraphic service are accuracy and promptness. These factors, in a great measure, determine for the telegraph its peculiar field. In the Morse system the presence of the human element in every operation necessarily introduces corresponding inaccuracies. In the Rowland system the human element is reduced to a minimum by keyboard transmission and automatic reception. The printed local record before the Rowland operator, too, shows what has been transmitted, and furnishes the operator an immediate method of checking the message sent. The octoplex wire capacity of the Rowland and direct transmission from typewriter keyboards with direct reception in printed characters on regular telegraphic blanks ready for immediate delivery constitute the best possible combination to insure promptness. With the Morse system, particularly in wet weather when the wire capacity is reduced, serious delays in transmitting telegrams often occur through a sudden or abnormal accumulation of business. The octoplex wire capacity of the Rowland system

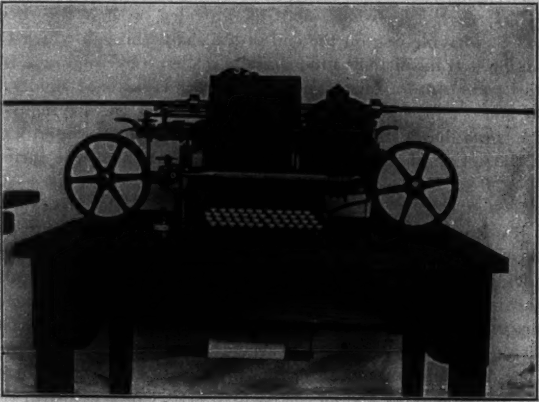


Fig. 12.—Correspondence unit, sending side showing keyboard and Home recorder.

in all weather conditions provides a greatly increased margin for reducing and avoiding such delays.

As already explained, the machine demanded by the telegraphic field must give greater efficiency to the operator and the wire than can be done with Morse methods.

The efficiency of a Rowland operator is practically double that of a Morse operator. To transmit a Morse message, two skilled operators are necessary, while to transmit a Rowland message one typist is necessary. The sole requirement that the operator shall be a typist and able to transmit a message intelligently greatly broadens the labor field and permits the economies incident to such an increased supply.

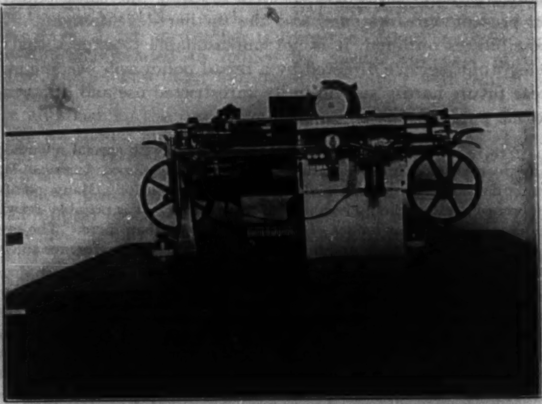


FIG. 13.—Correspondence unit, receiving side showing page-printer.

The more complete utilization of the wire operated by the Rowland, as compared with the Morse, has already been suggested. Under weather conditions most favorable to the Morse, the Rowland wire capacity is double that of the Morse, while in weather unfavorable to the Morse, the Rowland wire capacity is triple or quadruple that of the Morse.

As features of the Rowland system which lend themselves to further expansion and development in the telegraphic field, it is interesting to note that the method of dividing the use of a telegraph wire among a number of operators provides the fundamental and ideal requisite for the development of new and improved distributing methods for the general service and for facilitating and expanding the private use of the telegraph. Machine methods of relaying, more accurate and efficient in their operation than Morse methods offer further promising fields for greater efficiency.

In conclusion, having indicated the field and the demand for a machine telegraph and how the machine under consideration meets the conditions imposed, it only remains to suggest that with the application of machines, which provide for the more efficient transmission of a greatly increased business on present wire systems, and the further developments of the possibilities outlined, it is not unreasonable to expect that the telegraphic service directed by a broad policy will become in the near future hardly second in its unrestricted use and importance to the post office itself.

NOTE.—The above article has been written with special reference to American practice and in particular the highly developed American Morse methods and the highly skilled American operator. Many points of difference present themselves in foreign practice. It is possible elsewhere to use much smaller values of received current than here. The saving in wires becomes much greater when considered with reference to countries making use of other methods of transmission.

DISCUSSION ON "THE ROWLAND TELEGRAPHIC SYSTEM," AT NEW YORK, APRIL 15, 1907.

Ralph W. Pope: First I wish you to join with me in an expression of our appreciation of the esteemed privilege of having with us to-night our first honorary member, and I may say one of our oldest members, Sir William Preece, who has awarded to us the distinguished honor of presiding this evening.

When undertaking to open the discussion on the paper this evening, it was not my intention to go into the technical details of this very remarkable instrument which has been described in the paper before you. My first opportunity of examining this system was at the Paris Exposition in 1900, where it was on exhibition only, as we may say. On Saturday last I had an opportunity to examine the system in actual commercial operation between New York and Boston, and upon one of the worst days, so far as weather is concerned, that could be conceived, which tended to reduce the speed, not only of this system, but of any other system of telegraphy with which we are familiar.

In approaching the discussion of a system of this kind I wish to say we should first divest ourselves of the prejudice against the Morse telegraph, which exists in the case of those who are not practical operators and familiar with the code. To those who have practised Morse telegraphy, some of those things, which appear to be a mystery to others, are like an open book before us. I may say in explanation of my position on this subject that I learned telegraphy on the Hughes printing telegraph forty-nine years ago. I might make it fifty years, but I would not lie for one year. I learned the Morse telegraph as a side issue, simply as a man might pick up the art of playing the violin, without any idea that the Morse system would eventually prevail. The Hughes printer, which was new at that time, was invented by David E. Hughes, a musician in Kentucky, and one of the pair which I first operated was the second then in use, the first, I think, being between New York and Philadelphia, and the second, on which I learned, was between Great Barrington and Pittsfield, Mass., which at that time was an unimportant line. The contempt for the Morse and Bain systems which were in operation at that time may be well expressed by the terms applied to them by the printing operators. The Morse was called the "woodpecker," and the Bain system the "dyetubs"; and any message transmitted by either of these systems, *via* Springfield, was supposed to be "bulled", as the only system which was known to be "accurate and reliable" was the House printer, on which the Hughes was afterwards grafted. In those days, when an inventor brought out a new system a company was organized to exploit it. Consequently we had in the old times the magnetic, the House, and the Bain telegraphs. The House printing telegraph, the invention of Royal E. House, was a triumph of electromechanical skill. It is true that between New York and Boston it could not be worked through, on account of the rapidity of the vibrations, and consequently the Hughes printer, requiring but one pulsation to each letter, was preferred to the House and eventually superseded it I am giving these instances of the situation at that time.

Now, there is no doubt about the speed of the Morse, the House, or the Hughes, so far as a single wire was concerned. The House was perhaps the fastest, the Hughes next, and the Morse last. Eventually there came about a consolidation, and the House printer was displaced, the Hughes system was transformed by the late George M. Phelps into the "combination" printer, and subsequently into the "motor" printer and was in actual operation up to within a few years ago. It was duplexed, and I might say, although I will come to it later, that the expert operators on the Phelps printer, between New York and Boston, and New York, Philadelphia, and Washington, were the highest paid in the telegraphic operating department, so that we may cast aside for the moment the idea that because the letters are on the keys, any fool can be an expert operator.

The telegraph is the oldest, and I will also say the most important development of the modern applications of electricity. The electric light has its rival in gas, the electric railway has its rival in steam, and the telephone is applicable only to comparatively short-distance transmission; but, for world-wide communication, for the general distribution of intelligence, and that application of electricity which would be the last we would part with, telegraphy stands at the head.

The Morse system, as it is known to those who operate it, may be used under the most adverse conditions. Prior to the expiration of the Morse patents, which covered the application of the local circuit and the sounder, the opposition companies were obliged to use simply the relay without the sounder, so that we had to read from very faint sounds. On one occasion I was visited in Exchange Place by an operator from the old American office; it was a wet day, and I had my relay screwed down so that the sound of it was like the ticking of a watch. The office was about one-quarter the size of this stage, and the relay began to tick, and I said, "I am busy." He asked, "What are you doing?" I replied, "I am receiving from Boston." That was a fact; I was receiving on that relay without the local sounder and he, although only four feet away, could not hear a sound It might be assumed I was guessing at it, but I was actually reading it.

I am rather wandering over the subject, but I am bringing up the conditions that existed in regard to the Morse telegraph and why it prevails to-day In 1868 I was quartered in the Gold Room at the time of the "Black Friday" panic. The correspondent at the Boston or Philadelphia exchange was right at the counter. Assuming this platform as the exchange, the operator, if he had a message, would call out for the man for whom the message was intended, and he would come to the counter for his telegram. I have sent a message to Boston, and received a reply and delivered it to the original sender of the message, before the ink on the original was dry, probably in the course of a minute. Now, leading up to the instrument which we have under discussion this evening, I made a similar test with Dr. Sheldon, who was with me last Saturday; I sent a telegram to Boston, to be repeated back to New York and delivered to Dr. Sheldon, who was at my side. I handed him the following message in the course of regular business: "Samuel Sheldon, Boston—I will arrange Monday morning for payment suggested, and will adjust the matter with Mr. Carty as soon as possible. R. W. Pope." The message was delivered back into my hands, in printed form, having been sent from New York to Boston and returned from Boston to New York, in five minutes. As a practical demonstration, I am quite satisfied with that, for the reason that my reply was sandwiched in with other commercial messages received in the ordinary course of business, and I wish to say, as the result of our investigation, that four operators were sending to Boston over one wire, and the messages were coming in over the same wire on the four instruments from the Boston end. I consider this a very satisfactory showing.

There is a weaker point in the telegraph service than the simple transmission of messages, and that is the question of delivery after the message is received. In my earlier days, when I received a message, I used to close the office for a half hour, during which time I went out to deliver it. I have also known of cases when one messenger was in the office, when two messages were received, one message to go a mile in one direction, the other a mile in the opposite direction, and the question was which of the two messages should be delivered first. That leads up to another point, and that is the classification of service.

We have heard from the advocates of the telegraphic system, that all messages should be sent and delivered in the order of their reception, which is well known to be practically impossible. In the first place, the ordinary customer hands in his message over the counter, and it may go to a distant point over one out of perhaps ten or a dozen wires. If he happens to be a broker at the exchange, it may go over a special wire and be delivered in the course of a few minutes, while, if it goes in the ordinary course of business over a busy wire, the sender will be lucky if it is delivered in an hour. So that there are some things to be considered in regard to telegraphing outside of the transmission of messages.

Reverting to the system we have under discussion, we must understand that it applies in the main, as most of these systems do, that is, the machine or automatic systems, to the trunk line business, or business between any two large cities, where the volume of business is such that apparatus of this kind can be installed and kept in continuous operation. It appears to me that the general use of the Morse telegraph is due to its simplicity, low cost of operation, and its application to all conditions.

As I was saying in regard to my learning the Morse system as a side issue; after learning to read by sound, if the Hughes printer broke down we could send or receive a telegram through the bell on the side, using the Morse code. The Hughes printer was based on synchronism. The instruments at each end of the wire were required to be in almost absolute synchronism. If they varied, one of them "threw out," as we called it, and had to be put in unison and started up again. There was a very peculiar instance of the necessity of that unison that occurred to me at the time I learned the business, and that was on the occasion of the first message over the original Atlantic cable in 1858. My brother, who was my superior, had gone away for a day. I was on duty, and the station twenty-five miles north had been endeavoring for two hours to send me a communication which I could not receive on the Hughes printer. When the train arrived the newsboy on board set off a pack of fire crackers. I inquired what was up, and was told that the Atlantic cable was a success. My brother was on the train. He came into the office, and I told him what I had been doing; that the office twenty-five miles away had been trying to send something to me for nearly two hours, and that the printer continually "threw out." He looked at the machine, and took a hammer and knocked along the brake governor on the shaft about $\frac{1}{16}$ of an inch. The brake had shifted about $\frac{1}{16}$ of an inch on the shaft and did not strike in the center of the wheel; that was all the trouble. The machine was not quite fool-proof.

In closing, I call attention to the author's statement that: "In practical operation it has continuously demonstrated its efficiency in dispatching an enormous volume of business with regularity and accuracy on a single wire, while the operators employed have been not necessarily skilled in the use of the Morse code." That is quite true. They do not need to know how to fiddle or to play a snare drum, but all the same it is a fact that the Morse operator who is trained and familiar with the business, if he or she has learned the Morse code, they are adapted to telegraph work. So I find as a matter of fact, that the best operators, even the best operators to work a keyboard, are those who are trained in the telegraph service and have that intuition or familiarity with the business which makes them valuable employees. Consequently, while it is quite proper that they should be trained to do special work, in the ordinary office it is better to have the force interchangeable, and if there are Morse operators who are capable of operating the printer system, and operators of the printer system who are capable of operating the Morse system, the interchangeability of that force becomes a rather substantial consideration in the office organization; and I might go further and say that, while it is no doubt advantageous and economical to install a system which will convey a larger number of messages over a wire, it is still desirable that the systems should be interchangeable, that the simplicity of the Morse will persist, and, while it is true that the Morse telegraph has not been improved for many years so far as the operator is concerned and so far as the public is concerned, it has been improved so far as the company is concerned in regard to the greater earning capacity and by the use of the typewriter which has enabled the telegraph operator to receive at a higher rate than the sending operator can send the messages.

The speed of the Rowland system, and in fact all the claims set forth in this paper so far as the speed is concerned and in comparison with the Morse, I consider well substantiated. The speed of forty words a minute can be attained by a Morse operator, but it still remains to be seen whether we can develop a system which will send messages four in each direction at that rate ready for delivery, which is 320 words a minute over a single wire. The advantage of the delivery of messages in page form over the old tape printing system I consider is very desirable, and I am glad to know that the Rowland printer has reached its present state of perfection. I can hardly believe that the distinguished inventor would have asked that any better monument to his memory could be erected than the establishment and the continuation of a system bearing his name, and it is my hope that it may be continued and in the future be on an equality with the Morse telegraph of to-day.

A. E. Kennelly: It is remarkable that, although electrical applications have developed so rapidly and assumed so important a position in this and other countries, the electric telegraph has almost stood still. In fact, some say that it has not even marked time. A few years ago, in New York City one could pass through the main telegraph office and see a few printing telegraphs. One might have seen a number of automatic Wheatstone instruments, very likely a number of quadruplex sets. I think I am correct in saying there are now no printing telegraphs remaining except the recent ones of the system described here and one other new system; that there are no Wheatstone automatic sets, and that there are fewer quadruplex sets than there used to be. We are struck by the contrast between this apparent want of progress in telegraphy and the progress which has made itself felt in other lines of electrical advancement. It is, however, much easier to criticize destructively than constructively, and there are a number of influences which have been active in this country and elsewhere to account, in part at least, for this apparent want of progress.

First of all, the telegraph is the only apparatus which has maintained its original ground and kept on the earth. Everything else electrical has been driven off the earth. Telephones have been driven off the earth, to take shelter in metallic circuits. Even so huge a machine as the railroad motor has been virtually driven off the earth. The telegraph has stood, and at considerable disadvantage to itself, because it not only suffers from its own internal disturbances, but also from vagrant disturbances due to other systems in its neighborhood.

I think I am correct in saying that each man, woman, and child in the United States does not send more than about one telegram a year on the average. On the other hand, there are about five million telephones in the country, and the number of conversations by telephone of each man, woman, and child is something like two-thirds of a telephone message a day; this means a difference of, roughly, a message a year, and a message a day, in the two systems, respectively. It is the convenience and growth of telephony which has tended to keep progress in telegraphy in abeyance. The rate of growth of telegraph messages has been slower than the rate of increase of population, according to recent published reports. We seem to have reached rock bottom in the matter of economies. It does not seem possible to get a more economical operation of the system, and consequently anything which will enable us to rob the mails more than we do now, in the use of the telegraph, must be effected by some entirely new method. At the present time, there is not only the fixed charge upon lines and apparatus, but the cost of the operator's time at the originating station, at the intermediate stations, and at the receiving station. These costs seem to be impossible of elimination on the Morse system.

We cannot flatter ourselves that any system such as that which has been described to-night will eliminate the Morse system everywhere. The Morse system is admirably adapted not only for way traffic, but also for through traffic of not great pressure. We can only hope for something to take the place of hand telegraphy where the telegraph traffic is great and the pressure keen. If traffic is to increase, there can be but two ways of handling it. One is to duplicate the Morse circuits, to duplex and quadruplex them, if possible. The other is to have something entirely different. Here is a system which offers something entirely different. We must have something which will eliminate the telegraph operator on high-pressure trunk circuits. The hand Morse must be eliminated. The Wheatstone system did that in part, because it enabled a number of sending operators to work together on one wire, and the same number of receiving operators to work together on the same wire; but here is an apparatus which will enable the Morse code to be completely eliminated; a simple mechanism to be operated from both ends of the line, keyboard to keyboard, typewriter to typewriter. That is an ideal system, if the inertia of the removing parts can be reduced so as to make the speed of the same order as that which can be secured by instruments of the Bain type. I am sure we hope that this apparatus, and others of similar type, may so far develop as to bring progress once more to the neglected art of telegraphy, and let us have a chance to relieve the hands of the operators without reducing the demand upon their skill and intelligence.

William Maver, Jr.: It is true that telegraph engineers and managers admit that the ideal system of telegraphy is one in which the messages may be transmitted, without previous preparation, at a high rate of speed and be received accurately at a distant station on page form in printed Roman letters. There have been many difficulties in the way of producing this ideal system, and therefore the degree of success which has been reached by the Rowland system, and I might also say by the Buckingham, Barclay, and Murray systems, is most encouraging. I have long pondered on what set Professor Rowland's mind in the direction of multiplex telegraphy. I do not think it could have been the idea of making money, because we all know it requires the purse of a millionaire to bring into practical operation or even into fairly practical operation, a multiplex telegraph system. I have heard of one inventor who has spent more than $150,000 in the attempt to do so, and recently I saw a statement to the effect that $9,000,000 has been expended in the last decade in the attempt to perfect printing telegraph systems. I do not know that these figures are strictly accurate, but even if cut in half they would suffice to illustrate the point.

I had the pleasure of seeing Professor Rowland's original apparatus some years ago, and it certainly was somewhat crude. At that time if I remember rightly it was a tape printer. Before Professor Rowland passed away—too early I think—the system had undergone two complete changes, and since then I believe it has undergone four more radical changes. To-day it is in a very fair state of practical operation. I saw the system in operation, as Mr. Pope saw it, last Saturday, working between Boston and New York, on the lines of the Postal Telegraph Company. It worked very nicely. I think, however, that it is necessary to make some qualification or amplification of Mr. Potts' statement, with reference to the efficiency of this system in meeting the requirements of commercial telegraphy. In fact this system is in operation on one wire, about 280 miles in length, as an octoplex; that is to say, eight messages are transmitted by this system simultaneously at a certain rate of transmission. To apply this system to a circuit between New York and Chicago will most likely entail some modifications; as, for instance, the reduction of the capacity of the system from that of an octoplex to that of a quadruplex. It will also require the introduction of an automatic repeater midway of the circuit, the practicability of which has not as yet been tested out. As Mr. Pope has pointed out, the system is not applicable readily to way wires and certain other circuits. The capacity of the system is given as 600 messages per hour; this, it should be noted, is the maximum capacity of the system when operated as an octoplex on comparatively short overhead wires. On long circuits this capacity will be, it is probable, materially reduced.

There seems to be no question as to the utility of the Rowland system on the comparatively short circuits to which it has thus far been applied. The matter of general reliability, accuracy, and cost of operation of the system are probably yet to be determined. I believe Mr. Murray has intimated that he considers his system better adapted to long circuits than to short circuits, presumably because of the necessity for preparing the messages in advance for transmission, etc. On the other hand, it is possible that the Rowland system may find its best field on comparatively short lines.

The author states that the basis of the telegraph current used in this system is an alternating current. This is of course true. but it is a somewhat singular fact that the actual signaling currents are made up of pulsations of continuous or one-direction currents. This is evident from the oscillograms. The accuracy of this remark will also be apparent from the fact that if, for example, a signal is to be made by normally negative impulses Nos. 2 and 4, and if we assume that the impulse before impulse No. 2 was a normal positive impulse, then impulse No. 2, when it is reversed, will also be positive, which gives the desired reversal, so called. Similarly, impulse No. 4 will be preceded by a normal positive impulse. Consequently, when impulse No. 4 is reversed it will be followed by a normal positive impulse. Therefore in this and numerous other combinations for signals, there will be five successive positive or negative impulses. Hence the "clearing out" effects of alternating currents are not fully obtained. The currents used in signaling in this system are indeed virtually akin to those employed in submarine cable signaling.

The author states that the current strength necessary for the operation of the relays of the Rowland system is about 35 milliamperes. It is interesting to note that this is about the current strength required in the operation of the ordinary Morse duplex and quadruplex relays.

The author implies that the presence of the human element in the Morse system introduces corresponding inaccuracies. I have the honor to differ somewhat with him in what he implies in that statement. It has long been an axiom among telegraph managers and engineers that the receiving operator of the Morse system is a continual check upon the sending operator. In many cases in actual practice the receiving operator instantly detects and corrects or prevents errors of the sending operator, as well as the errors or omissions that would be frequently caused by momentary line trouble, and which no mere machine at the receiving end could do.

At first sight, this highly ingenious telegraph system may appear somewhat complicated. This impression, however, wears off with a clearer knowledge of the apparatus; for it is apparent that the seeming complexity is due more to the necessary multiplication of the parts than to the intricacy of the system as a whole. The engineers of the Rowland system are to be congratulated on the success they have thus far achieved. They are fortunate in now having the system in operation under practical conditions, where its defects, if any remain, will become apparent and when opportunities for further development and improvement of the system will doubtless be found.

Henry G. Stott: In reading over this paper, it occurred to me with a great deal of pleasure that to-night I was to take part in a meeting at which Sir William Preece was to preside. I experience this pleasure largely because over twenty years ago, when I studied electricity under Professor Andrew Jamison, our text-book on telegraphy was one by Preece and Sieveright. Now we come to the fountain-head for more information on the subject of telegraphy. I think if we had the book here to-night it would be found that very little has been written into the progress of the art since that volume first became a text-book.

Several of the public-service corporations have recently been forced to increase their rates. No board of directors deliberately sits down and increases the rates for its service just for the pleasure of doing so; the only thing that prompts them to do this is in the realization of a grave duty to the stockholders. True, the cost of copper has gone up 100 per cent., and the cost of labor 50 per cent., in the last ten years. But why is it that telegraph rates have had to be increased, while electric-light rates, power rates, and telephone rates have all gone down?

Some time ago Mr. Pope called to my attention a letter which he received from a telegraph engineer in the West. The letter was in the nature of a complaint against the Papers Committee, of which I am a member, and said: "Why do you have so many papers on lightning arresters, electric railway motors, and things of that kind, and you never give us a paper on telegraphy?" I shall try to answer that letter here.

Why do the other gentlemen, who present elaborate papers on lightning-arresters, railway problems, features connected with transmission lines, etc.—why do they come here with these papers? Simply to get the benefit of the criticism and comment of their co-workers in these fields. How many papers have we had presented on telegraph subjects in the last ten years? I think this is the first one that I can recall; but I trust that it is only the precursor of many equally important papers, that the period of stagnation in the development of telegraphy is at last at an end, and that the rapid development by our members of automatic apparatus, such as that described in to-day's paper, will enable our telegraphic companies to progress as rapidly as the other electrical industries.

E. F. Northrup: I have in hand a small piece of paper which speaks of the human side of the development of this system of telegraphy. I am reminded that it will be six years to-morrow morning since Professor Rowland died. Mr. Maver said this evening that he wondered why Professor Rowland turned his attention to telegraphy. I think I can answer that question, for I was with Professor Rowland at the time that he began to be interested in this telegraph. I acted as his assistant in its development for three years previous to his death and I had the exceptional pleasure of spending two weeks with him at his cottage at Seal Harbor, Maine, and there heard from him why he devoted himself to the development of his telegraph system. He had a disease which he knew would probably be fatal and he could not get a life insurance. He told me he had many problems in physics of the highest importance that he would love to work out, but that he felt that it was his duty to try to leave his family a heritage that would have a monetary value. He was the most courageous man that I ever have known. He worked on his telegraph almost to the day before his death, as this paper will attest. Three days before his death I received this note written by him on his sick bed:

> Put in patent condenser, also coils; duplex of many lines so as not to interfere with each other. You do not know this; come and learn.
> H. A. R.

I went to his house and got his instructions while he was on his sick bed.

I worked on the telegraph for a year after his death, but I cannot take time to speak at length regarding the technical features of this system with which, at one time, I was very familiar. I may say, however, that the system is peculiar in this respect, that it is a kinetic system as distinguished from a static system. I mean by this that normally current is passing over the line at all times and not at a time only when a signal is being sent. The system presents, however, this paradox: that when a signal is being sent at the same instant from opposite ends of a duplexed line, there is at that instant no current on the line. The signal is made by stopping the vibrating tongue of a relay, while in most other systems a signal causes a relay tongue to move.

One feature, not spoken of to-night, is the immense flexibility of the system in the matter of the distribution of the lines and messages. Professor Rowland laid the foundations of innumerable methods for the distribution of the messages which the flexibility of the alternating current admits.

Gano Dunn: It is some years since I used to pound a key, but I love it still and trust I may be pardoned a tribute of affection to the telegraph business, because the telegraph business opened to me the door of a college education and an electrical career. It took me from a dingy office haunted by messenger boys to this glorious building which speaks a development of the electrical industry far beyond the dreams of the early telegrapher. The old Morse systems had in their ranks nearly all the men who later started this electrical development and I feel proud that I am, as it were, a member of the old union. It is fitting that this first evening of the week of dedicatory exercises should be devoted to a telegraph meeting.

If the paper presented to-night were read by the general public, especially the paragraph which rates the capacity of the new system at 600 messages per hour, the public would be inclined immediately to ask Mr. Clowry, who in the newspapers a few days ago explained the increase in rates of our large telegraph companies, how long it will be before these rates shall be again reduced to a very small amount, in view of the enormous difference between 600 messages per hour per wire and 17 messages per hour which he referred to. If not qualified, this paper would give the public a false impression. It is not the capacity for transmission that limits the telegraph business to-day, for actual transmission is the least part of all the business involved in the receipt and delivery of messages. The Rowland system, beautiful as it is, a system which I believe will come into large use, is, after all, applicable only to trunk lines between large cities, to places where there are experts to watch it and places where its use will be justified by the volume of business.

I doubt if the Rowland system will ever drive out the old instruments. Their simplicity and reliability have won for them their present place. The fact that we still have them testifies eloquently to their fitness. It does not testify to stagnation in the technical development of telegraph systems.

In the Rowland system the typist takes the place of the operator, but the typist is seldom qualified to rearrange damaged or displaced parts; and these things happen sometimes in a telegraph office when the manager's back is turned, for boys occasionally throw ink-wells that put the apparatus out of business. I have seen 150-ohm relays and the rest of the accompanying Morse outfit unmindful for years of everything that was thrown at them.

The grounds for the statements I made of the limited field to which the Rowland system may look forward are in the proportion already existing between quadruplexes and single lines. Roughly speaking, there are 30,000 offices in this country. Notwithstanding the fact that the quadruplex is cheap and yet increases the wire capacity nearly four times, I doubt if there are 3000 quadruplexes in use. If there were the great demand for increased wire capacity, which the advocates of the machine-telegraph and multiplex systems generally take as their starting point, we should see more quadruplexes. The proportion mentioned indicates the balance between the advantages gained by their introduction and the accompanying disadvantages of inflexibility and complications.

Although the Rowland system increases the wire capacity eight times that of a single wire, and claims an increase in operator capacity about three times, and makes further claim to increase in operator capacity by not requiring a receiving operator (although making no allowance for the skilled mechanician that would be needed) I believe that these great advantages will be almost counterbalanced by the enormous complication of the apparatus. If Mr. Kipling should write up the telegraph business, the Rowland system is what he would call an eight-day clock.

I think the success of the Rowland system must be looked for in large offices where there are trained experts, and a high degree of organization. It is my opinion that for many years to come ninety per cent. of the clicks we shall hear over the length and breadth of the land will be good old "Morse."

Sir William Preece: I think the hour has arrived when we had better close this discussion, but it will afford me an opportunity to play the same role that Mr. Pope has played and to refer to my early years and the memories of the past. My career commenced in the year 1852, so that I have had 55 years' experience, while he said 49; he was afraid to say 50, like the man who shot 999 ducks and would not admit that he had shot the thousandth. Fifty-five years' experience in all branches of practical telegraphy gives me the privilege and honor of saying that I have had something to do, directly or indirectly, with every single practical application of electricity. I commenced first with the telegraph, and my heart still goes out to the telegraph. In my early days I was brought into contact with Faraday—I believe I am to-day the only living pupil of Mr. Faraday. My early acquaintance with Dr. Kennelly was in poring over Faraday's Researches. In 1853 we laid down underground wires between London, Liverpool, and Manchester, 212 miles long, and we had serious effects due to static induction. We did not understand it. We called in Faraday and Sir George Wren, who was then the Astronomer Royal, and I worked with these two great philosophers for many months and carried out all the experiments Faraday wished to have carried out. I still have some of the records.

The first automatic system of telegraphing was that invented by Bain. The currents were transmitted through punched paper, and marks made on strips of paper saturated with prussiate of potash. They were blue marks, and I have many of the records made in those days to show the influence of static induction in retarding and in elongating the currents that came out at the distant end when a mere dot was introduced at the sending end. Many years after this, my first acquaintance with Edison arose from his coming over to England with an automatic system based on this chemical recorder. He had placed at his disposal a cable coiled in one of the tanks in the cable makers' works. He asked me what I thought would be the length of a dot through a thousand miles of cable. I had in my mind a thousand miles of cable laid out straight, and I told him

I thought a dot would come out about six inches long. He said, " What do you think it would be in the case of a cable coiled in a tank?" I said, "I really cannot tell." "Why," he said, "I wanted to know what the length of that dot would be; and when that dot came out, what do you think it was? It was 28 feet long!" That was Edison's experience with the effects of static induction. It was an experience of great service to those who are transmitting currents through long underground cables. That led to a very extensive system of underground cables, and no doubt we shall learn a good deal of the influence of the alternating current in working to great distances. I commenced with an automatic system that transmitted 1500 words a minute. It was competent and capable of transmitting 3000 words a minute. Why didn't we use it? Because there was no business for it. This question of automatic versus manual telegraphy is, after all, a question of business, a question of the number of words one wants to transmit, not the number of words one can transmit. In the last fifty years I have been engaged in developing automatic systems of all kinds, but the one in which I am peculiarly interested is the Wheatstone system. When I left the post office service in 1889 we had worked up the Wheatstone system so that it would give 650 words a minute on our longest circuit. We did not want 650 words, for the simple reason we did not have 650 words a minute coming in. It is a question of the messages to transmit, and those having practical knowledge of the working of the telegraph system know this: that in the telegraph business of a country there is a curve precisely similar to the curve we know so well, the load curve of the generating station, for whatever purpose it is used. Messages come pouring in according to the business hours of the day. In England we have a peak load every morning between 11 and 12 o'clock. It subsides during luncheon hour, and comes up again in the afternoon. In England there is only one time over the country, here in America there are four times, Eastern, Central, Mountain, and Western, and consequently there are peaks at different times of the day. There is three hours difference between San Francisco and New York; the result is the load curve for business in this country is different from the load curve in England, and therefore no fair comparison can be drawn between the rate at which the messages are transmitted per day or per wire, between the two countries. In the last analysis what is wanted is the very best system that will carry the work through to the best advantage of those who use the telegraph.

I discussed this question some years ago with Dr. Green when he was president of the Western Union Telegraph Company. This is my fourth visit to the United States, and whenever I come, my first object has always been to visit the two telegraph companies and learn what progress they are making. I come here to learn, and, if I see things done in a manner that is contrary to my judgment, I do not hesitate to criticise them; on the other hand, if I find things meritorious and worthy of commendation, I adopt them on the other side and give full credit to those who have produced them on this side of the water. In discussing these things with Dr. Green, he said to me, in the decisive manner he had, "In this country time is our only competitor." What he meant was, that the time elapsing between the moment the message was written and the moment it was delivered, was the time they wanted to control, that was the only thing he feared.

In England I think we have the automatic system in a state of perfection. I do not think there is any system that will beat the Wheatstone for business as it is. It may be that if we increase our load-curve and get a load-factor for the whole day of 50 or 60 or 70 per cent., then we will want automatic systems. At the present time there is no real need in our part of the world—I do not know what it may be here—for any automatic system which will send more than 200 or 300 words a minute, and that we have. It may be that the business will increase and necessitate such a thing. Automatic work is essensential and absolutely imperative on submarine cables, but submarine cables are different from the aerial wires we use. There is a great distinction between telegrams which are always short, and news work which is very considerable at times. In England it is enormous. In England our news business is much greater than in this country. We are all in a compact little island. There is not a single country town of any magnitude that does not issue an evening paper full of news sent by automatic telegraph, and there we find that 400 words a minute is ample to supply all the newspapers with what they want. It won't come in any quicker. A man making a speech, who wants it to appear in the next morning's paper, does not speak over 110 to 120 words a minute. I am not speaking to you now at a rate of more than 110 words a minute, and if there were a shorthand writer here who was reporting my remarks for the purpose of sending them to Chicago, for instance, it would not require an instrument that could work 1500 words a minute to send 110 words a minute. I want to point out that however new and perfect an automatic system may be—and I must say this is a beautiful instrument—there will always be some features concerning it which may not be entirely satisfactory. I had a good deal of correspondence with Dr. Rowland on this very subject, as he was anxious to make a start in England. We lost him too early, as he was one of the most brilliant scientific men of the age. His work will live for many years.

I take it the effect of the discussion to-night has really been, not to bring out very strongly the relative merits of manual telegraphy and automatic telegraphy; but it has raised this one question, and a very important question, and that is the value of labor in the telegraph service. In our younger days, Mr. Pope and I, when we used the key, thought ourselves howling swells because we could not only send messages, but we could absolutely and instinctively see a fault or error. When you are at your instrument, you know it like you know your child or wife. The instinctiveness with which an experienced telegraphist can trace a fault is quite wonderful. We take a great deal of pride in our knowledge, but it has this great defect in our country—it has caused our telegraphists to suffer from that complaint which is generally called " swelled head." There has been a good deal of trouble over there. The tendency has been to develop as much as we possibly can these automatic systems rather than to bring down the gentleman whose size of hat increases rather too frequently. It is rather a misfortune, but the development of the brain, in the great growth of business, is one of those things which cannot be helped. I think Mr. Dunn referred to the complication of these systems. That of Dr. Rowland is a combination of others. The synchronism was invented by Hughes; the breaking up of a circle into several divisions transmitted by switch systems was invented by Bain. It was tried a good deal and made practicable by Baudot in Paris, and it is working over submarine cables between Paris and London with a considerable amount of success. You have the alternating current introduced by Crehore and Bedell. There is really little novelty in the principles used, but there is considerable ingenuity shown in the mechanical arrangements. One likes to see a good thing worked up and put into practice. I have done a great deal in introducing automatic apparatus. It seems that we all want to meet the views of Dr. Green. We want to lick time. We can only do that by having means to transmit a message as rapidly as possible from the sending end to the receiving end. The conception of using a wire for many circuits, octuple, as in the Rowland system, is certainly a very great advantage. The reason why the quadruplex has not grown much in England—and I do not think it has grown much in this country—is because of the fault that it " throws out," and you lose the advantage of quadruplexing with four circuits, or octuplexing with eight circuits. Therefore, a fault on the line with these systems is very serious. That is the reason why there is a tendency to fall back on the duplex method. The tendency was to use copper very much for speed, but the price of copper has gone up so much it has rendered that practically impossible.

I am sorry to have kept you so long. I have been exceedingly interested to-night in taking part in this discussion. It has been one of the principal studies of my life, as I have told you, and it is like renewing one's childhood almost, to come back here and take part in a discussion of something that I studied over fifty years ago. I can only repeat what I said, that my coming to-night has been a source of great pleasure to me. I come here and meet familiar faces, some of whom I meet on the other side, and many more, perhaps, that I meet only when I come here. I find that marine architecture has done much to make the journey across the Atlantic a matter of luxury. Brittania is said to rule the waves, but marine architecture to-day rules the spirit of the waves. We passed through three very severe gales. We never had the fiddles on the table, and I never saw a sick person on the ship. One is in a beautiful palace for five or six days,—it will soon be four and a half days—from Liverpool to New York. I imagine in the future it will be a simple thing for a man to come from England, attend one of your meetings, and the next day take a steamer back home. There is one thing in which you fellows beat us horribly, and that is in your delightful hospitality. It is not mere hospitality, it is not the fact of the hospitality, but it is the way you do it. I do not know why it is, cannot tell you, but I assure you every time I cross the Atlantic and come here I find the gentlemen treat me in such a pleasant way that if I am spared I will come over again as soon as I can get away. I again thank you most heartily for all the courtesies which have been extended to me by your members.

A paper read at a meeting of the Schenectady Branch of the American Institute of Electrical Engineers, April 25, 1907.

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CONSTANTS OF CABLES AND MAGNETIC CONDUCTORS

BY ERNST J. BERG

In the paper on "Line Constants, Etc.,"* equations were given for the inductance and capacity of the parallel conductors used in transmission lines. The formulas given were sufficiently accurate for any transmission line calculations where the distance between wires is large compared with their diameters; where, however, the diameters are comparable with the distance, as is often the case with cable transmissions, it is necessary to use the strictly theoretical expression.

In looking up the available literature on this subject, one is surprised at the great number of different formulas given. This is particularly the case in reference to the inductance formula which generally consists of two terms, one of which is constant and is usually given as 0.5, 0.75, or 1; the other a logarithmic function, also variously expressed.

Frequently the constant term is left out altogether, especially in formulas pertaining directly to standard line constructions.

To clear up the situation the following deductions are made. and a discussion added to show when the approximate formulas can properly be used.

A and *B* in Fig. 1 represent a couple of parallel cylinders of radius r and distance between centres D. For convenience in reasoning it is assumed that they are made up of a large number of strands or elements.

A current I flowing through conductor *A* will set up magnetic fields inside of the conductor and in the surrounding space. Consider at first the flux inside of the conductor.

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*PROCEEDINGS, A. I. E. E., September, 1907, p. 1409.

The flux per unit length of line in section $d\,x_1$ is due to the current flowing inside of zone $d\,x_1$, which current is $\frac{x_1^2}{r^2} I$.

Thus the magnetomotive force per unit is $\dfrac{\frac{x_1^2}{r^2} I.}{2\,\pi\,x_1}$

The field intensity is $4\,\pi \times$ magnetomotive force $= \frac{2\,x_1\,I}{r^2}$

Therefore the flux $= \frac{2\,x_1\,I\,d\,x}{r^2}$

The electromotive force corresponding to this flux $= k \times$ flux in each section $= \int_0^r k \times \frac{2\,x_1\,I\,d\,x_1}{r^2} \times \frac{x_1^2}{r^2} = k\,\frac{I}{2}$. The equivalent flux corresponding to this electromotive force is $\frac{k\,I}{2k} = \frac{I}{2}$, and therefore the equivalent inductance, which is $\frac{\text{flux}}{\text{current}} = \frac{1}{2}$.

The flux outside of the conductor is found in a similar way. In that case the magnetomotive force per unit length is $\frac{I}{2\,\pi\,x}$ the field intensity $4\,\pi\,\frac{I}{2\,\pi\,x} = \frac{2\,I}{x}$ and the flux

$$M_0 = \int_r^{D-r} \frac{2\,I}{x}\,d\,x = 2\,I\,({}^{n}lg\,(D-r) - {}^{n}lg\,r) = 2\,I\,{}^{n}lg\,\frac{D-r}{r}$$

The total flux expressed in centimeter-gramme-second units is therefore $M = I\left(2\,{}^{n}lg\,\frac{D-r}{r} + \frac{1}{2}\right)$ and the inductance

$$L = \frac{M}{I} = 2\,{}^{n}lg\,\frac{D-r}{r} + \frac{1}{2}\,.$$

Transforming this equation to practical units and expressing L in millihenrys per mile of conductor we get:

$$L = \frac{161}{10^3}\left(2\,{}^{n}lg\,\frac{D-r}{r} + \frac{1}{2}\right)$$

In transmission lines D is usually large compared with r, so that the equation may be written:

$$L = \frac{161}{10^9}\left(2\,{}^{n}\!l\,g\,\frac{2D}{d} + \frac{1}{2}\right)$$

where D is the distance between centers of wires and d their diameter.

Determination of capacity between two parallel cylindrical conductors. Let A and B in Fig. 2 represent two conductors charged with a certain amount of electricity Q, A being positive $+Q$ and B negative—Q.

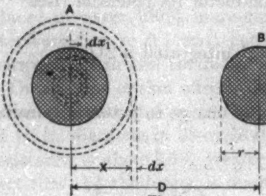

Fig. 1

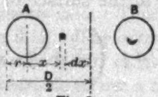

Fig. 2

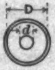

Fig. 3

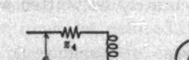

Fig. 4

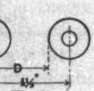

Fig. 5

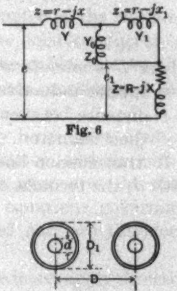

Fig. 6

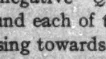

Fig. 7

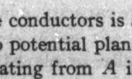

Fig. 8

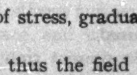

Fig. 9

Around each of these conductors is a field of stress, gradually decreasing towards zero potential plane.

The total field emanating from A is $4\pi Q$, thus the field intensity of an element at any distance x from A is $\frac{4\pi Q}{2\pi x}$ or $\frac{2Q}{x}$

The corresponding field intensity due to the charge in B is— $\frac{4\pi Q}{2\pi (D-x)} = -\frac{2Q}{D-x}$, so that the resultant static field intensity or static potential is:

$$\frac{2Q}{x} - \frac{-2Q}{D-x} = 2Q\left(\frac{1}{x} + \frac{1}{D-x}\right)$$

Consequently, in moving the element from the plane of zero potential to the surface of the conductor its potential rises to $\int_r^{\frac{D}{2}} 2\,Q\,d\,x \left(\frac{1}{x} + \frac{1}{D-x}\right)$ which integrated is $2\,Q\,{}^{n}l\,g\;\frac{D-r}{r}$.

The capacity, which is the ratio of charge to potential causing the charge, is therefore

$$C = \frac{Q}{2Q\,{}^{n}l\,g\,\frac{D-r}{r}} = \frac{1}{2\,{}^{n}\,l\,g\,\frac{D-r}{r}}$$

which in practical units is:

$$C = \frac{890\,k}{10^4\,{}^{n}l\,g\,2\,\frac{D-d}{d}}$$

where C is microfarads per mile of conductor
k specific inductive capacity,
D distance between centers of wires,
d their diameter.

In transmission lines where $K = 1$, and $2D$ is large compared with d, the formula can sufficiently accurately be written as:

$$C = \frac{890}{10^4\,{}^{n}l\,g\,\frac{2D}{d}}$$

Cables. With the present state of the art it would not be conservative to use a cable at more than 25,000 volts between conductors, although it is to be expected that at least with rubber-covered cables, or cables with insulation of gradually decreasing specific inductive capacity, a higher voltage can finally be used.

At present time essentially, or almost entirely, two kinds of cables are used, one having paper insulation and the other rubber insulation, both being covered with lead.

Although the dielectric strength of paper is considerably less than that of rubber and therefore more insulation is needed due to the lesser cost, it is almost entirely used, and no doubt will remain so until cables for higher voltages are required.

It is almost impossible to give a general rule for the safe current capacity of a cable, since it depends largely upon what kind of conduit is used, the relative amount of insulation, etc. Perhaps 0.025 watts per square inch radiating surface (outside) is as fair approximation as can be made. When, however, the cable is laid directly in soil, 50% more current can be carried, and when placed in water 100% more current seems safe. This last case corresponding to 0.1 watt per square inch. The actual rise in temperature in the conductor is then about 30° cent.

On account of skin effect it is not desirable to use a conductor larger than about 1 in. in diameter in 60-cycle circuits, and one of 1.5 in. diameter in 25-cycle circuits, in which case the effective resistance is about 10% greater than the ohmic resistance. The fact that the conductor is made up of a number of small wires does not materially lessen the skin effect, since the individual strands are not thoroughly intermixed, but each remains at the same distance from the center at all times.

There is, however, for given outside diameter of the cable as compared with the outside diameter of the solid conductor, a slightly lesser skin effect in the case of the cable, due to the higher specific resistance of the cable, when considering the total cross-section.

In other words, there is less conductivity for a given area of cable than in the same area of solid conductor, and since the skin effect depends upon the resistance per given area the skin effect must be reduced. The theoretical equations governing this phenomena are extremely complicated and are therefore omitted.

The inductance and capacity equations deduced apply directly as long as all conductors belonging to the same circuit are in the same conduit or cable. If, however, that is not the case, but as in a single-conductor cable independent cables are used for the outgoing and incoming conductors "effective" values have to be calculated.

In the preceding were given the inductance and capacity formula for two parallel cylindrical conductors. In dealing with cables we require to consider the inductance and capacity between concentric conductors, such as single conductor in lead-covered cable where current is permitted to flow in the lead or concentric conductors in general. In that case the equations become

$$L_{m\,h} = \frac{370}{10^3}\ {}^{10}\log\frac{D}{d}$$

$$C_{m\,f} = \frac{770\ k}{10^4\ {}^{10}\log\ \dfrac{D}{d}}$$

Where L and C are respectively inductance in millihenrys and capacity in microfarads per mile of conductor. Thus in a concentric single-phase cable in 0.5 mile of length of cable or in a three-phase cable in 1 mile of length.

Effect of grounded lead covering of single-conductor cables. The lead covering obviously acts as a short-circuited secondary to the electromotive force induced by the reactance of the line. It consumes some of the electromotive force, therefore reduces the inductive drop but increases the ohmic loss due to the currents in the lead.

In calculating the phenomenon we will substitute for the line the primary of a transformer of same resistance as the line and with a magnetizing current the same as the line current at the voltage corresponding to the reactance electromotive force.

The reactance of the primary in this equivalent transformer is caused by the flux between lead covering and the conductor and is therefore as a rule quite small.

The secondary resistance corresponds to the resistance of the lead (which for given cross section is 14 times that of copper), the reactance is the same as that of the primary.

We can therefore diagramatically show these circuits as in Fig. 4.

The lead covering being grounded acts as a sheet of metal surrounding the conductor in inductive relation to the primary.

Or as in Fig. 5, where the line resistance and reactance are assumed as concentrated in a transformer.

Or finally as in Fig. 6, as a combination of inductive circuits with the proper transformer constants.

Let e = line voltage.
$Z = R - j\,X$ = load impedance.
$z = r - j\,x$ = primary impedance.

where r = line resistance.

x = reactance between conductor and lead.

$z_1 = r_1 - j\,x_1$ = secondary impedance.

where r_1 = resistance of lead covering (For the same cross-section 14 times that of copper.)

Y_0 = primary admittance = $j\,b$ where

$$b \text{ is } \frac{I}{E_x} = \frac{1}{x_0} \text{ or } Y_0 = \frac{j}{x_0}$$

x_0 = line reactance if no lead covering existed and a conductor of the same outside diameter as that of the lead covering were used in the calculations.

$$z_0 = \frac{1}{Y^0} = -\frac{j}{b} = -j\,x_0$$

Joint admittance of the two parallel circuits of impedance z_0 and z_1 is $Y_0 + Y_1 = Y_2$. The corresponding impedance z_2 =

$$\frac{1}{Y_0+Y_1} = \frac{1}{\frac{j}{x_0}+\frac{1}{r_1{}^1}} \text{ since } x_1 \text{ is small}$$

$$\text{we have } z_2 = \frac{r_1\,x_0}{j\,r_1+x_0} = \frac{r_1\,x_0\,(x_0 - j\,r_1)}{r_1^2+x_0^2}$$

Total impedance is $= z_2+z+Z$

Current therefore $= \dfrac{e}{z_2+z+Z}$

Voltage across load $e_1 = \dfrac{e\,Z}{z_2+z+Z}$

$E_1{}^1$ = drop in line $e - \dfrac{e\,Z}{z_2+z+Z} = \dfrac{e\,(z+z_2)}{Z+z+z_2}$

Let $z+z_2 = z_3$

We have then $E_1^1 = \dfrac{e\,z_3}{Z+z_3} \quad \ldots\ldots A$

In an ordinary line we have

current $= \dfrac{e}{Z+z_4}$. Drop in line $E_1^1 = \dfrac{e\,z_4}{Z+z_4} \quad \ldots B.$

Comparing these two equations, A and B, we see that if the values of line impedance obtained by writing $z_4 = z_3$ are inserted we can use the ordinary line equations

$$Z_4 = r_4 - j\,x_4.$$

From above we have—

$$Z_4 = z_3 = z + z_2 = r + \frac{r_1\,x_0^2}{r_1^2+x_0^2} - j\left(x + \frac{r_1^2 x_0}{r_1^2+x_0^2}\right)$$

or neglecting x, which is small, we can write the effective resistance as—$r + \dfrac{r_1\,x_0^2}{r_1^2+x_0^2}$

and the effective reactance $= \dfrac{r_1^2\,x_0}{r_1^2+x_0^2}$

As a rule x_0 is small compared with r_1 and we can write

$$\text{effective resistance} = r + \frac{x_0^2}{r_1}$$

$$\text{" reactance} = x_0$$

When estimating the reactance and effective resistance of a grounded single-conductor lead-covered cable—calculate the ohmic resistance r of the conductor, the ohmic resistance r_1 of the lead covering, (specific resistance 14 times that of copper) determine the reactance x_0 as between two parallel conductors of same diameter as the outside diameter of the lead, and substitute the values so obtained in the equations given above.

Instance. Two cables of 1000 ft. total length placed on 4.5 in. center, each cable contains a 0000 B. & S. conductor. Outside diameter of lead 1 in., inside diameter 0.75 in. What is the effective resistance and reactance of 25 and 60 cycles?

$r = 0.049$, area of lead $\frac{1}{8}\pi\frac{7}{8} = 0.343$ sq. in. corresponding to copper section $= \frac{0.343}{14} = 0.0245$ sq. in.

Therefore $r_1 = 0.332$.

At 25 cycles reactance outside of lead is $\frac{2\pi 25}{10^3}\times\frac{161}{10^3}$

$$\left(2\ {}^{n}lg\frac{8}{1}+\frac{1}{2}\right)\frac{1}{5.28} = 0.0223 \text{ ohms.}$$

Therefore effective resistance

$$= 0.049 + \frac{0.0223^2}{0.332} = 0.0505 \text{ ohms.}$$

At 60 cycles the reactance is 0.0535.

Therefore effective resistance = 0.0572.

The resistance is increased 3% in the first case, 16% in the latter.

To illustrate the increased loss in a single conductor lead-covered cable, table *A* has been prepared. It applies to a single-conductor cable No. 0000 B. & S. having a lead covering $\frac{1}{16}$ in. thick, the outside diameter of the lead covering is 1 in. Losses are given for various distances to return conductor and at various frequencies.

It shows that in general the losses introduced are small and need only be considered in 60-cycle systems when the cables are a considerable distance apart. This table refers to one mile of conductor.

Cycles				12.5
Distance inches	2.13	4	12	24
r	0.264	0.264	0.264	0.264
$x_0 = x_e$	0.0249	0.0458	0.0772	0.0952
x_2^0	0.0006	0.0021	0.0059	0.009
r_e	0.2642	0.2649	0.2665	0.2678
Increase	0.1%	0.34%	0.98%	1.4%

Cycles			25	
Distance inches	2.13	4	12	24
r	0.264	0.264	0.264	0.264
$x_0 = x_e$	0.0497	0.0916	0.1544	0.1904
x_0^2	0.0025	0.0084	0.0238	0.0362
r_e	0.2651	0.2676	0.2743	0.2796
Increase	0.42%	1.37%	3.9%	5.9%

Cycles		60		
Distance inches	2.13	4	12	24
r	0.264	0.264	0.264	0.264
$x_0 = x_e$	0.1193	0.220	0.3706	0.4570
x_0^2	0.0142	0.048	0.137	0.208
r_e	0.2701	0.2848	0.3233	0.3536
Increase	2.3%	7.9%	22.5%	33.9%

Effect of a non-grounded lead covering in single-conductor lead cable. Since there is a difference in flux between the inside and the outside half of the lead covering, currents must flow alongside the covering in one direction in the inside half, in the other direction in the outside half.

The average distance between center of one conductor and the nearer half of the lead covering of the other conductor is

$$D - \frac{D_1}{4}$$

The average distance to the outer half is

$$= D + \frac{D_1}{4}$$

The difference in inductance is therefore

$$l_d = \frac{742}{10^3}\left({}^{10}\log \frac{D + \frac{D_1}{4}}{d} - {}^{10}\log \frac{D. - \frac{D_1}{4}}{d} \right)$$

$$= \frac{742}{10^3}\ {}^{10}\log \frac{D + \frac{D_1}{4}}{D - \frac{D_1}{4}}$$

Where l_d is expressed in millihenrys per mile of conductor.

With I current flowing in the conductor and the resistance of the lead covering calculated as above, that is a conductor of same length, as the conductor proper, and with the actual cross-section of the lead, we get:

$$\text{Reactance electromotive force} = \frac{2\,\pi\,n\,l_d\,I}{10^3}$$

$$\text{and eddy currents in lead} = \frac{2\,\pi\,n\,l_d\,I}{4\,r_1\,10^3}$$

$$\text{Thus the loss in the lead} = \frac{4\,\pi^2\,n^2\,l_d^2\,I^2}{4\,r_1\,10^6}$$

Therefore the effective resistance

$$= r + \frac{n^2\,l_d^2}{r_1\,10^5}$$

Where n = frequency
l_d = inductance in milhenrys
r_1 = lead resistance—as defined above.
r = resistance of conductor proper.

With 4 in. distance between centers and one inch conductor, we get:

$$D + \frac{D_1}{4} = 4.25$$

$$D - \frac{D^1}{4} = 3.75$$

$$l_d = \frac{742}{10^3}\,{}^{10}\log 1.13 = \frac{40}{10^3}\text{ mh.}$$

Therefore effective resistance

$$= 0.049 + \frac{25^2 \times 40^2}{0.33 \times 10^6 \times 10^5} = 0.04903.$$

We see from this that the eddies in a single conductor lead covered cable are negligible if the lead is not grounded.

Effect of iron-armored single-conductor cable. If the cable instead of being covered with lead, were covered with a magnetic material such as iron, the problem would be more complicated on account of the increased flux due to the iron. Such conduit is indeed quite out of the question on account of the increased reactance and eddy losses.

From the saturation curve of the iron it is possible to determine the magnetic density and therefrom the flux in the iron for a given current in the conductor.

Assume this flux to be M

E, the electromotive force corresponding to this flux is

$$\frac{4.44 \times M \times n}{10^8}$$

The corresponding reactance is $\frac{E}{I}$

which reactance should be added to the normal reactance as obtained in a non-magnetic system.

The hysteresis loss corresponding to this density is found from the hysteresis curves of the iron, and this loss divided by I^2 gives an equivalent resistance which should be added to the resistance as obtained in case of a non-magnetic conduit.

As an instance. Assume the cable described above covered by iron instead of lead, and that 150 amperes are flowing in the main conductor.

Assume further that the iron is $\frac{1}{8}$ in. thick and that the total loss due to eddies and hysteresis is five times as great as the hysteresis loss proper.

The magnetomotive force available is $150\sqrt{2} = 212$ ampere-turns.

The magnetic length is $\frac{7}{8}\pi = 2.75$

Magnetomotive force per inch $= \frac{212}{2.75} = 77$

This corresponds to a density of 100,000 lines per sq. in.

The magnetic cross-section $= 1000 \times 12 \times \frac{1}{8} = 1500$ sq. in.

Therefore the total flux $M = 150{,}000{,}000$ and $E = 166$ volts,

the reactance due to iron is thus $\frac{166}{150} = 1.1$ ohm.

From hysteresis curve we find the loss per cubic inch per cycle = 0.028 watts.

Therefore the loss is $0.028 \times 5 \times 1500 \times \frac{7}{8} \times \pi \times 25 = 14{,}500$ watts.

Whereas the $I^2 R$ proper is but $150^2 \times 0.049 = 1100$ watts.

It can readily be proved that even the thinnest iron covering is prohibitive in single-conductor cables for alternating currents.

In concluding the discussion of the effect of armor we may add that where two or more conductors involving a complete circuit are carried in the same conduit, it matters not whether the covering is of iron or lead, grounded or not grounded. The effect of the covering on the resistance or the reactance is negligible.

Iron wire and cables used as electrical conductors. Since the ohmic resistance and permeability of iron changes very considerably in different grades and since the permeability varies with the current, it is evident that it is very difficult to lay down any definite rules regarding the effective resistance and reactance. So that in order to get accurate determinations it is necessary to test samples of the conductor intended to be used.

With the present price of copper wire, it is evident however that wherever small power is carried relatively short distances at high voltages, iron wire, or at least iron cables, could be used, and calculations must be made before the actual wire has been secured.

With direct current the matter is fairly simple, since the permeability does not enter and wires of definite resistance could be ordered. This resistance in iron wire varies from say four times that of copper to seven or eight times that of copper.

With alternating current the skin effect causes additional resistance, which, at least in large conductors, is considerable, often several times that of the true ohmic resistance. This effect is however small in small wires, say wires of number 8 to 12 B. & S. gauge, but with large wires it is considerable. Such small wires can not, however, well be used for transmission lines for mechanical reasons. Therefore, it seems probable that stranded cables only need to be considered.

From a number of deductions it would seem as if the effective resistance of such stranded cable (7-strand cable) could be expressed by the following formula:

$$R = r + \frac{K\ N\ B^2\ D^2}{r\ 10^5}$$

In which K depends upon the permeability and may average 2.

R = effective resistance per mile of cable.
r = ohmic resistance.
N = frequency.
B = current density in amperes per square inch superficial area
D = external diameter of the cable.

The reactance can be approximated as:

$$X = x + 0.01\,N + \frac{K\,N\,B^2\,D^2}{r\,x\,10^5}$$

Where X = effective reactance per mile of wire.
x = reactance as obtained if the cable were made of copper.

These formulas apply fairly well, at least to cables of from ¼ in. to ½ in. external diameter. It is unlikely that larger cables will be used, since the skin effect is very considerable with ½ in. cables, and it is unlikely that smaller cables will be used, on account of mechanical reasons.

It is to be noted in connection with these formulas that the reactance as a rule is not prohibitive with the use of iron cables. It has often been thought that the reactance was the limiting feature, but this is not the case—the effective resistance is of more importance.

When using very large iron or steel conductors, such as rails in the case of single-phase railroading, the effective resistance can be estimated from the degree of penetration of current, and this has been approximated by Steinmetz and others to be

$$\delta = \frac{2000}{\sqrt{g\,\mu\,N}}$$

Where δ, the penetration, is expressed in inches.

g = electrical conductivity, which with soft iron is about 110,000, μ is the permeability and might be about 500 and N is the frequency.

Consequently, the resistance of such large iron and steel conductors does not depend upon the actual cross-section, but upon the perimeter. It is furthermore proportional to the square root of the frequency.

[For additional discussion on this paper see page 926].

A paper presented at the 218th Meeting of the American Institute of Electrical Engineers, New. York., April 26, 1907.

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THE TELEPHONE WIRE PLANT

BY SERGIUS P. GRACE

Telephone engineering has been looked upon by many engineers as principally a switchboard problem. The switchboard problem was undoubtedly deserving of the great amount of attention given to it by telephone engineers, and the results are everywhere evident to-day in the perfect working mechanisms of the modern, central battery switchboard. An analysis of the construction costs of the telephone plant will, however, show that from two-thirds to three-fourths of the total expenditure is required for the outside plant; that is, for conduits, poles, cables, and wire. Because of the very large proportional expenditures for the outside plant, it becomes evident that the systems of line distribution should be most carefully studied in order that the best service may be given at the lowest cost.

In considering a telephone plant for a community, the first thing to be done is to decide upon a proper development plan for the growth of the business for a reasonable number of years. In view of the rapid advances in the telephone art and the possibilities of the introduction of new systems of transportation and communication, it would seem that fifteen to twenty years is as far ahead as we are justified in planning telephone development. If the plant is to care for service offered during this period, it must be originally so laid out and designed that the additional subscribers can be taken on without the redesign and reconstruction of the plant From time to time the development plan can be revised so as always to keep it from fifteen to twenty years ahead of the plant. In laying out a telephone development plan for a city, there are many things to be considered. The growth in population for the last ten years must be carefully considered; from all possible sources of information a prediction should be made of the population for the next ten to twenty years. It next becomes necessary to determine upon the percentage of development which may reasonably be expected; that is, the ratio of telephones in use to the population. This will vary considerably with the prosperity of he community and whether there are large manufacturing districts employing low grades of labor. It seems certain that this development in the ultimate will lie between 15 and 30 per cent. of the total population. A careful estimate must also be made of the ratio of line to stations. Thus if a very high party-line development is expected, the ratio of lines to stations will be low. To-day the telephone line really means more to us from the wire plant standpoint than the number of telephones. Formerly we used to consider the number of telephones as affecting the wire plant; now it is the number of lines. Because of the introduction of private branch exchanges two or three trunk lines may care for fifteen or twenty telephones, or there may be a number of telephones on one line, so it is the line in which we are interested.

After having looked over the city in a general way and obtained the best available data regarding the industries and the growth of the population in various parts of the city, the next thing to do is to resort to a detailed count of all the buildings, and block by block make an estimate of the number of telephones expected at the end of various periods during the next twenty years. In addition to the count of the present buildings, an estimate should be made of the probable ultimate number of the various classes of structures in each built up block of the exchange area. In providing for the number of lines to be installed at once, which at the same time should provide for two or three years' growth, the present number of lines in each block should be determined and to this number about one-third more lines should be added. This will vary in different cities and must be the subject of a special study in each case.

After having made a study of each block in the exchange area and determined the probable number of lines and stations at the end of each five year period during the next twenty years, the entire number of lines and stations as shown by the block map should be summed up and carefully compared with the ultimate figures deduced from the general development plan which is based upon the character of the city and the probable growth in population. If the estimates arrived at by the general development scheme and the detailed block scheme do not compare favorably, both estimates should be gone into again most carefully to determine the possible errors. In Fig. 1 is shown a section of a city of about 40,000 inhabitants. On this map are marked the numbers of the various classes of houses. At the left of the block in circles are shown present number and at right are shown ultimate number of houses. In Fig. 2 are shown the number in five years and ultimate number of lines in each block.

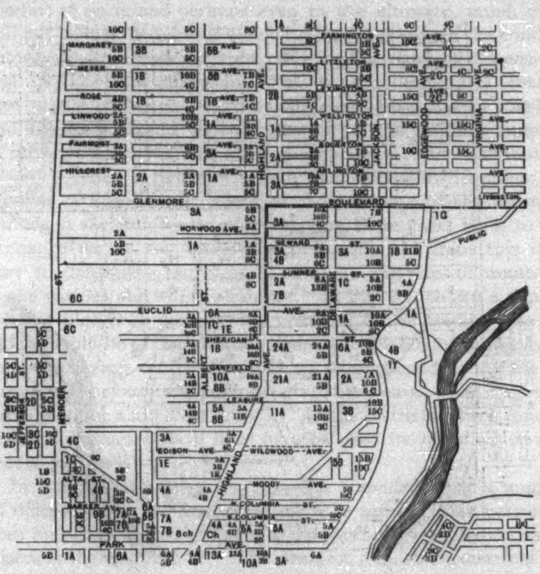
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FIG. 1—Development plan. Present ultimate number and classes of houses in each block

When the number of telephones in each block for the twenty year study has been decided upon, it remains to determine the most economical grouping of these telephone lines into exchanges. In small cities where the number of telephone lines in the ultimate will not exceed 8,000 to 10,000, it is reasonably certain to assume that one exchange will prove the most economical. If the district is very much scattered or very much elongated this is not true, and the proper number of exchanges should be determined in a manner to be described later. If one exchange is decided upon, a location for this exchange must be determined which will make the subscribers' line wire mileage a minimum. The determination of this centre with extreme precision is a problem for the calculus. The most simple case is when the streets are all rectangular, in which case the mathematical centre of distribution is found by drawing

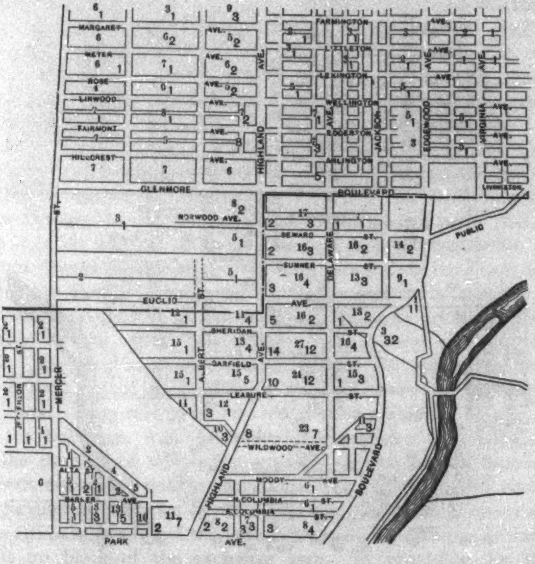
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Fig. 2—Development plan Number of lines in five years and ultimate number of lines in each block

lines at right angles through the exchange area, so that the number of telephones in the ultimate on each side of the lines is the same. If the present centre is a considerable distance from the ultimate centre, a mean centre between the two should be decided upon.

When the centre is determined, a complete conduit system should be laid out, touching at least one side of every block in the exchange area. It will never be necessary to construct all this conduit at once, and perhaps even in the ultimate, much of it will not be installed, but if a definite plan is prepared the conduit extensions from time to time will be of correct dimensions and in the right direction. This conduit must, of course, feed to the exchange centre by the most direct routes possible, and the lines should be concentrated in the smallest number of subways which will not affect the efficiency of the distributing system. Since it is known from the development plans the number of lines in each block at the present and the ultimate periods, a skeleton feeder plan carrying these pairs back to the exchange centre can readily be prepared, and from this it is easy to determine the number of ducts and sizes of manholes in the various parts of the subway. In Fig. 3 is shown a typical conduit plan. In general, the terminal cables feeding into the block should be of the ultimate size, while the feeder cables back to the exchange centre should be so proportioned as to care for the growth in business for from two to five years. Fig. 4 shows a cable plan for a five-year growth. In the districts where conduit is not constructed, pole lines may be used for distribution and feeder purposes.

In the case of a large city where it is evident that a number of offices will be required to furnish the service, it is a very complex and complicated problem to determine how many exchange districts there should be. The cheapest number of districts will vary as follows:

1. With the grade of talking transmission.
2. With the subscribers mileage—varies directly as the number of offices.
3. With the *A* and *B* position equipment—varies directly as the number of switchboards.
4. With the multiple jacks—varies inversely as the number of switchboards.
5. With the rent—varies directly as the number of offices.
6. With the office constant—varies directly as the number

of offices. This office constant takes care of the equipment which is common to all offices, such as the charging dynamos, storage-batteries and power boards.

7. With the central-office labor—varies directly as the number of offices.

8. With the trunk mileage—varies directly as the number of offices; also on number of calls per line and per cent. of trunking.

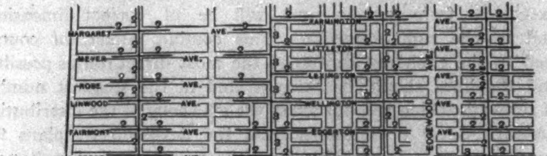
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Fig. 3—Development plan. Typical underground conduit layout

Good telephone service is fundamentally based upon good talking efficiency. The means for transmitting the talk is what the telephone company really furnishes to the subscriber. In very large city districts, because of the distances between the central offices, the cost per message is materially increased on account of the high-grade trunk plant required to give the subscribers good transmission. The central battery system of subscribers lines has proved very efficient and economical from service and maintenance standpoints. There is, however, a considerable loss introduced into each line by the ohmic resistance which operates to cut down the flow of current through the transmitter. In addition, then, to the attenuation loss present in all cases we have added to this in the transmitting loop, a loss due to the reduction of the current through the transmitter.

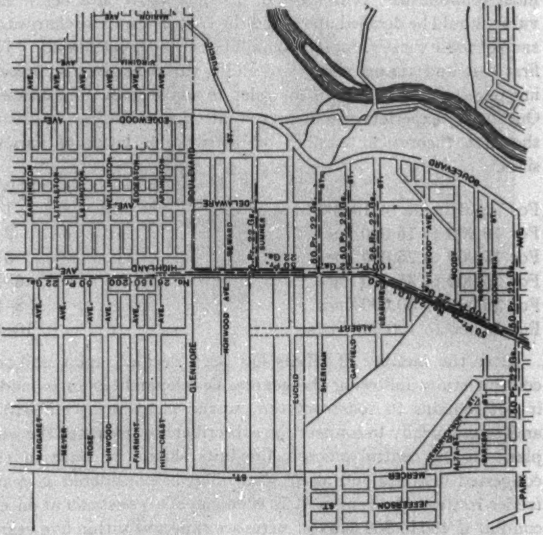
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FIG. 4—Development plan. Cable plan for five years' growth

In designing the subscribers lines, 22-gauge cable should be used as much as possible. In the case of a large city with a number of central offices there is a limiting resistance for the subscribers' lines which can not be exceeded without making the trunking plant very expensive. This limiting resistance of the subscribers' lines will vary in different cities because of the varying distances between central offices which affects the trunk line mileage. In general the subscribers' and trunk line plant must be so designed that, while there will always be good talking transmission between the subscribers, the annual charges on both the subscribers' and trunk line plant will be a minimum.

To lay out a city in the correct number of districts all the items above mentioned must be given careful consideration. From past experience it is generally possible to predict approximately the number of districts which will be found most economical. A number of districts above and below this value should be decided upon, and the costs and annual charges for each of these three groupings should be carefully calculated. The first cost and annual charges of all the variables given on preceding pages must be known in order to make these comparisons. Our past experience indicates that the following is about the best theoretical number of districts for cities of various sizes.

	Offices.
For an ultimate of 10,000 lines or less.	1
For 10,000 to 15,000 lines.	2–4
For 15,000 to 25,000 lines.	5–8
For 25,000 to 35,000 lines.	6–10
For 35,000 to 50,000 lines.	8–12
For 50,000 to 100,000 lines.	10–16

After the number of offices has been decided upon, and the conduit study following the general development plan is made, it yet remains to construct the outside plant so as efficiently and economically to connect the subscribers by means of the wire plant to the central offices. Conduits should be built in the congested districts and along what may be considered as main feeder routes. In general it is economical to construct at once a conduit if 400 to 800 pairs of wires are expected within five years. In the vicinity of the underground conduit system every effort should be made to connect the subscribers without resorting to aerial construction. Where the buildings are large and permanent and an average of ten telephones per building may be expected, the best method of construction is a cable directly into each building from the nearest manhole in the main conduit system. In the case of large office buildings one or more building cables should be run vertically in the wire or pipe shafts and terminal boxes provided at each floor, to which can be connected the individual wires for each telephone. The scheme

FIG. 5—Standard cable terminal

for distributing these individual wires most to be preferred is the hall molding scheme. These hall molding troughs should connect to the terminal box on each floor so that the wires to each telephone may be run from time to time as needed. This system is cheaper to install and easier to maintain than the conduit system following electric light practice. In many cities there are large area ways under the sidewalks, and a cable run through these area ways from one building to another and provided with a tapping terminal on each property makes a very good form of distribution.

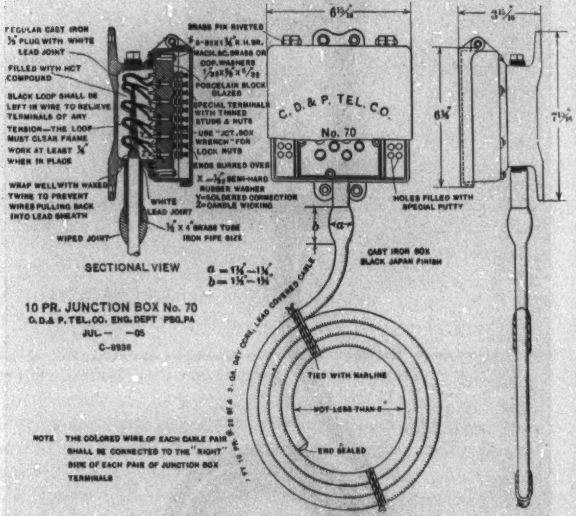
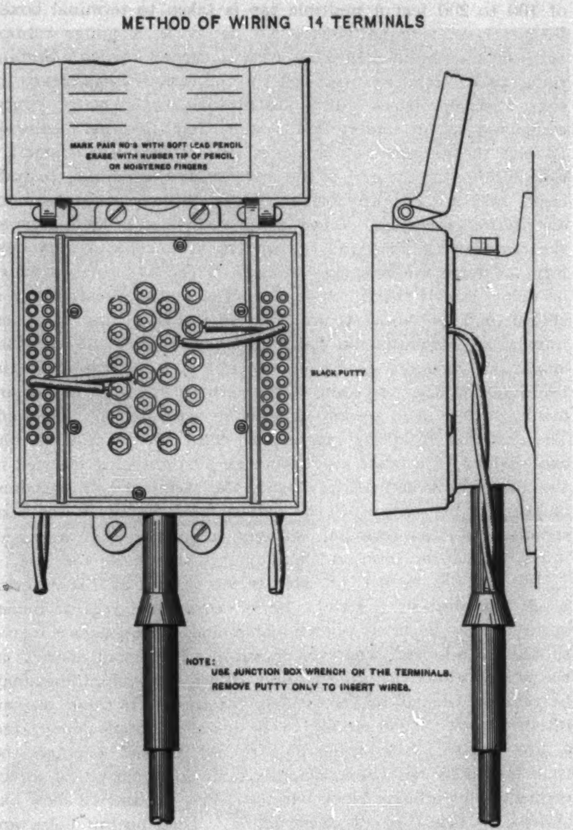

REGULAR CAST IRON ½" PLUG WITH WHITE LEAD JOINT
FILLED WITH HOT COMPOUND
BLACK LOOP SHALL BE LEFT IN WIRE TO RELIEVE TERMINALS OF ANY TENSION—THE LOOP MUST CLEAR FRAME WORK AT LEAST ¼" WHEN IN PLACE
WRAP WELL WITH WAXED TWINE TO PREVENT WIRES PULLING BACK INTO LEAD SHEATH
WIPED JOINT
WHITE LEAD JOINT
BRASS PIN RIVETED
#8-32X1¼" R.H.BR. MACH.SC.BRASS OR COP.WASHERS 1/32X⅜X5/32
PORCELAIN BLOCK GLAZED
SPECIAL TERMINALS WITH TINNED STUDS & NUTS
USE "JCT.BOX WRENCH" FOR LOCK NUTS
ENDS BURRED OVER
X—1/32" SEMI-HARD RUBBER WASHER
Y=SOLDERED CONNECTION
Z=CANDLE WICKING
½" X 4" BRASS TUBE IRON PIPE SIZE
SECTIONAL VIEW
$a = 1\frac{3}{8}"-1\frac{1}{4}"$
$b = 1\frac{1}{2}"-1\frac{3}{4}"$
6 15/16"
3 15/16"
6⅜"
7 15/16"
C. D. & P. TEL. CO.
No. 70
HOLES FILLED WITH SPECIAL PUTTY
CAST IRON BOX BLACK JAPAN FINISH
a
b
7 FT 10 PR. #22 B.&S. GA. DRY CORE, LEAD COVERED CABLE
TIED WITH MARLINE
NOT LESS THAN 8"
END SEALED
10 PR. JUNCTION BOX No. 70
C.D.& P. TEL. CO. ENG. DEPT PBG. PA
JUL.— —05
C-8936
NOTE THE COLORED WIRE OF EACH CABLE PAIR SHALL BE CONNECTED TO THE "RIGHT" SIDE OF EACH PAIR OF JUNCTION BOX TERMINALS

Fig. 6—Details of standard cable terminal

Where the blocks in the vicinity of underground conduit are well built up, but where none of the buildings is large enough or important enough to warrant direct connection the interior block system may be used to great advantage. In this system one or more underground laterals from the main subway system are run into the interior of the block and terminated on the


METHOD OF WIRING 14 TERMINALS
MARK PAIR NO'S WITH SOFT LEAD PENCIL
ERASE WITH RUBBER TIP OF PENCIL
OR MOISTENED FINGERS
BLACK PUTTY

NOTE:
USE JUNCTION BOX WRENCH ON THE TERMINALS.
REMOVE PUTTY ONLY TO INSERT WIRES.

FIG. 7—Wiring diagram of cable terminal

rear walls of the most substantial buildings. Around the interior walls at a height preferably not over ten feet from the ground are cleated lead-covered dry-core cables. At intervals of 100 to 200 feet a multiple tap is taken to terminal boxes. From these terminal boxes No. 18 B & S. gauge rubber-covered and braided-bridling wire is carried through bridling rings spaced about four feet apart to the various entrances to the subscribers' premises. This distributing cable is of course connected to an underground cable from the main subway. In case the number of telephones within the block is small, a terminal box at the end of the underground cable may be sufficient, and nothing but bridling wires through rings used for distribution purposes. Since no protection is needed between the distributing lines and the underground cable, a very neat form of terminal box may be used. The type of box which is being largely used for this service at the present time is shown in Figs No. 5, 6, and 7. In this box the wire terminals are mounted on hard-burned porcelain A five-foot length of dry-core lead-covered cable is connected to the terminals on the porcelain blocks, after which the blocks are firmly seated on a gasket of wicking saturated in compound. The cast-iron retaining case is then filled with compound, the cable wiped to a brass nipple, and an air-tight plug inserted in the top. This hermetically seals the terminal. On account of the durable nature of the materials employed in the construction of this terminal; namely, porcelain, cast iron and brass, the depreciation and maintenance should be very low.

In Figs. 8, 9, 10, 11 are shown examples of interior block distribution This type of construction is so inconspicuous as to be rarely objectionable, and in consequence its use should be adopted wherever possible. In certain districts in the neighborhood of underground subways, the buildings may be very old or may be very widely scattered. In these cases an interior block system could not be installed to advantage, and a low ring-top distributing pole should be used, pending the time the block will be sufficiently built up to permit of direct connection or interior block wiring. Figs. 12 and 13 show examples of this type of construction. Distributing poles are useful for furnishing connection between the underground system and the subscribers' premises during a period when direct connection or interior block wiring is not warranted. Ultimately, it seems certain that the distributing pole is bound to go.

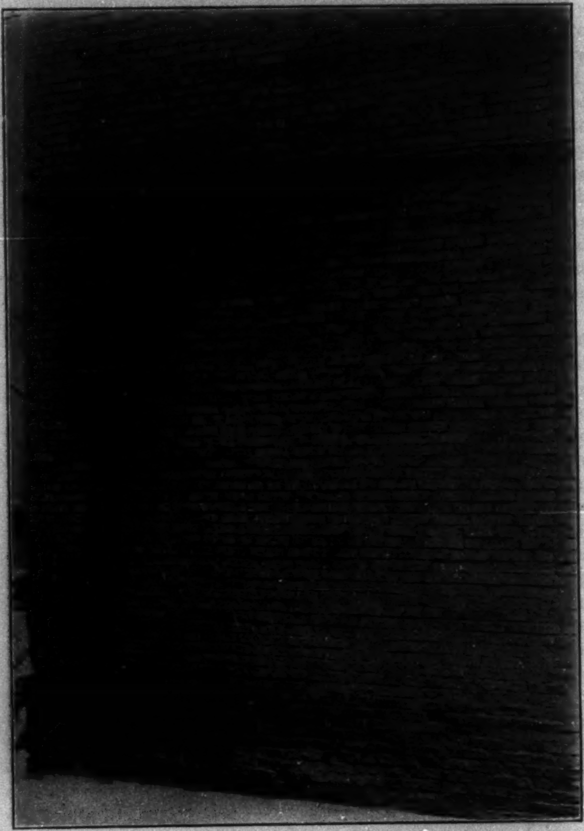
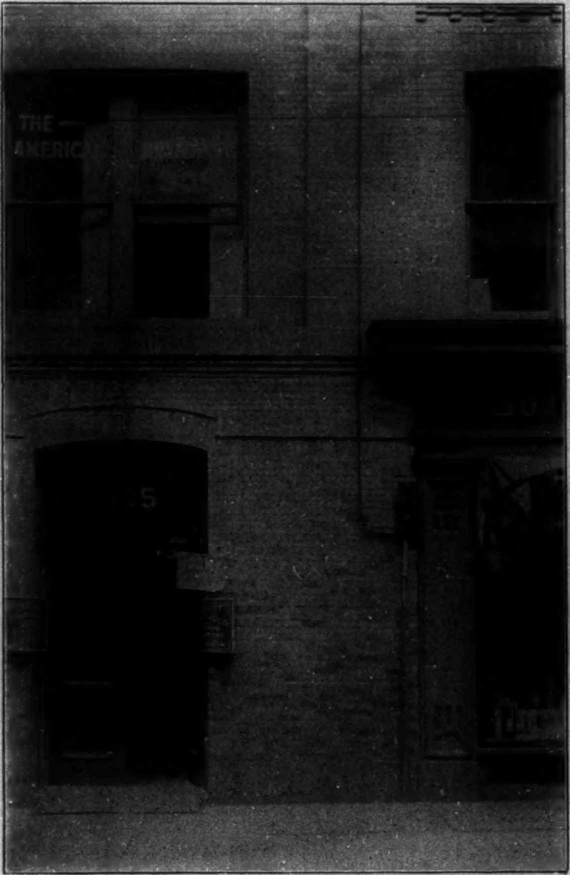


FIG. 8—Interior block distribution Sub-duct cable terminal and wiring runs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5

FIG. 9—Interior block distribution Example of wiring run to upper floors of building

A very large proportion of telephone service must be given in scattered residence districts where the number of circuits is so small as not to justify conduit construction. If conduits were installed at once, the construction plant costs would be very materially increased and consequently the cost of service to the subscribers would have to be increased. It is therefore necessary to determine what is the most economical, efficient, and sightly form of aerial distribution. In the early days of the telephone it was but natural that the distribution of the telephone wires should follow the same practice adopted by the telegraph companies. Very soon it was found that the number of telephone wires multiplied very rapidly, which required towering poles, equipped sometimes with as many as twenty cross-arms. The invention of the dry-core, lead-covered cable furnished relief for these lines, although for many years it was the custom to use as much open wire and as little cable as possible.

In the territory about Pittsburg the topography of the ground is exceedingly rough. This results in winding streets and almost an entire absence of alleys. To construct very large open wire lines in these winding streets was early seen to be impracticable, and when the great expansion of the telephone business began in 1897 it became imperative to design other methods for aerially distributing telephone lines. The system which was finally worked out and decided upon is that known as the aerial cable or all-cable system which was adopted in 1897 and has been our standard type of aerial construction ever since. In this system, very low poles are used, rarely exceeding 30 to 35 feet in height. These distributing lines are placed in alleys if they are available. A cable is strung near the tops of the poles and on alternate poles are placed 10- or 15-pair terminals. Each pair in the distributing cable appears in from two to four terminals, and common pairs are so laid out in adjacent terminals that it is easy to provide for party lines. The multiplying is so arranged that when the cable becomes crowded it may be cut into two or four parts, all pairs appearing in each part, and relieved by feeder cables. No cross-arms or bare wires are used for distribution along the lead, but from the binding-posts in the cable terminal a twisted pair, rubber-covered, and braided wire is strung directly to a point within the subscriber's premises. The use of this well insulated twisted pair wire very materially reduces the maintenance. An aerial cable system of

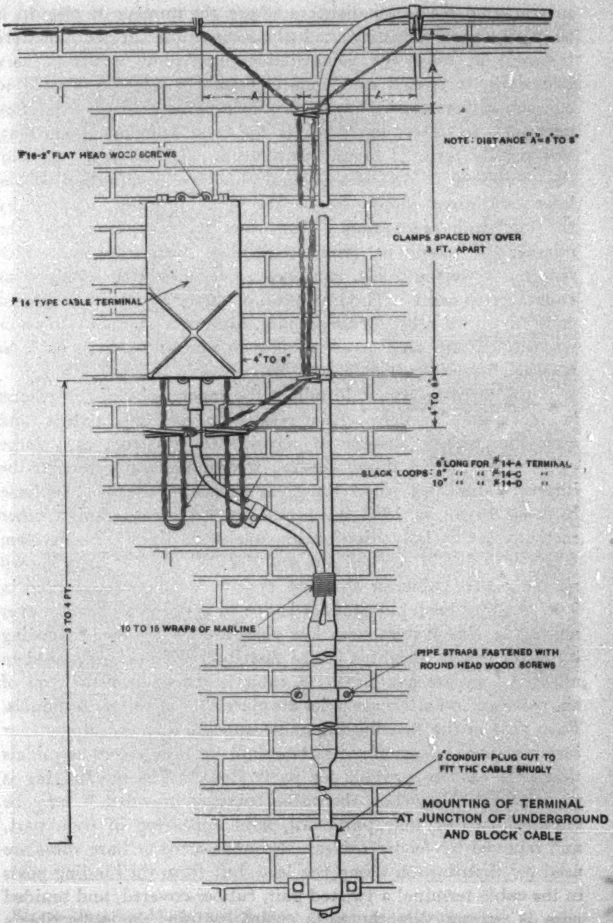

A
A
A
NOTE: DISTANCE "A" = 6" TO 8"
#16-2" FLAT HEAD WOOD SCREWS
CLAMPS SPACED NOT OVER 3 FT. APART
#14 TYPE CABLE TERMINAL
4" TO 6"
4" TO 6"
SLACK LOOPS: 6" LONG FOR #14-A TERMINAL
8" " " #14-C "
10" " " #14-D "
3 TO 4 FT.
10 TO 15 WRAPS OF MARLINE
PIPE STRAPS FASTENED WITH ROUND HEAD WOOD SCREWS
2" CONDUIT PLUG CUT TO FIT THE CABLE SNUGLY
MOUNTING OF TERMINAL AT JUNCTION OF UNDERGROUND AND BLOCK CABLE

FIG. 10—Interior block distribution. Details of cable terminal-connections on wall of building

this kind with twisted pair wires leading directly to the subscribers' houses is undoubtedly the most sightly form of aerial distribution, since all the cumbersome and troublesome open wires are done away with. In Figs. 14, 15, 16, 17, and 18 are shown methods and materials used in aerial cable construction. Attention is called to the grooved insulators used for supporting the twist wires. Each wire of the pair occupies a separate groove, thus preventing a crossing of the wires, which sometimes injures the insulation when there is a heavy strain on the wires.

FIG. 11—Interior block distribution Suspending wires from building to aerial cable terminal on pole

There has been considerable discussion among engineers regarding the life of twisted-pair, rubber-covered distributing wire. Rubber and paint are somewhat alike, in that all kinds of mixtures are sold under their names. From the very beginning we have been careful to specify a reasonably high grade of rubber and to insist on making tests of all wire submitted to us, to be sure that our specifications have been complied with. Very good wire was thus obtained, and samples which we now take down after having been in use for seven to nine years still show an insulation resistance of 200 to 400 megohms per mile when submerged in water. If the ordinary type of market wire, which is mainly intended for inside wiring, is used, the life will be much shorter. A good quality of rubber distributing wire well protected with a heavy braid should prove serviceable for ten or fifteen years.

Until recently the type of distributing wire most generally used was made of No. 14 B. & S. gauge copper. This size of wire was not necessary for conductivity, for as a rule it was connected to a 22- or 19-gauge cable pair. This size of wire was required for mechanical strength, because the wire was strung in spans and had to be self-supporting. During the past year there has been put on the market a copper-clad steel wire which is made by a new method. Copper is welded to a steel ingot and the copper and steel drawn out uniformly together. From all the examinations we have been able to make it seems that there is a perfect union between the copper and the steel. A No. 17 B. & S. gauge copper-clad wire having

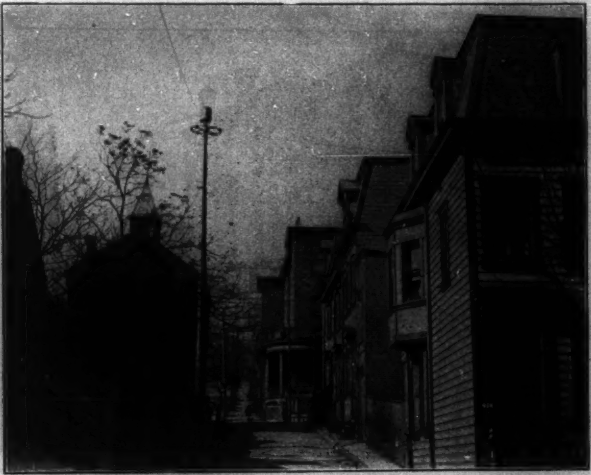


FIG. 12—Distribution of subscribers' lines from circle top distributing pole

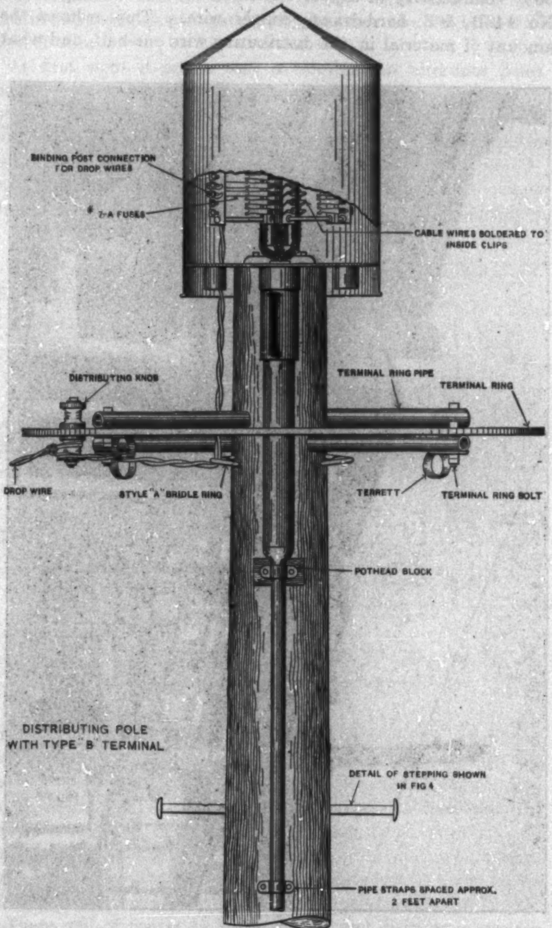

BINDING POST CONNECTION FOR DROP WIRES
# 7-A FUSES
CABLE WIRES SOLDERED TO INSIDE CLIPS
DISTRIBUTING KNOB
TERMINAL RING PIPE
TERMINAL RING
DROP WIRE
STYLE "A" BRIDLE RING
TERRETT
TERMINAL RING BOLT
POTHEAD BLOCK
DISTRIBUTING POLE WITH TYPE "B" TERMINAL
DETAIL OF STEPPING SHOWN IN FIG 4
PIPE STRAPS SPACED APPROX. 2 FEET APART

FIG. 13—Details of circle top distributing pole

30% conductivity of copper has the same tensile strength as a No. 14 B. & S. hard-drawn copper wire. This reduces the amount of material in the distributing wire one-half, and what is still more important, on account of the reduced area, decreases the amount of expensive rubber compound required to surround the wire. The amount of braided covering is also mate-

FIG. 14—Aerial cable distribution Cable top and drop wires to residences

rially reduced. The finished wire is very light and easy to handle and costs approximately 30% less than the No. 14 B. & S. type of wire.

At first sight it seems that a terminal on alternate poles must be expensive, and that terminals farther apart and with intervening distribution made by bare wire, would be cheaper. In order to determine this point clearly, a study was made some time ago showing a comparison between aerial cable distribution with taps on alternate poles and with twisted pair direct to the houses, as compared with aerial cable supplemented with bare-wire distribution. Various densities of telephone distribution were assumed, and it was found that in nearly all cases the system with taps on alternate poles was not only cheapest in first cost but also in annual charges. Where the distribution was very dense it was found that a tap on every pole was the most economical. As a general principle it would seem that we should carry the telephone circuits just as far as possible in cable and make the subscriber's drop of minimum length.

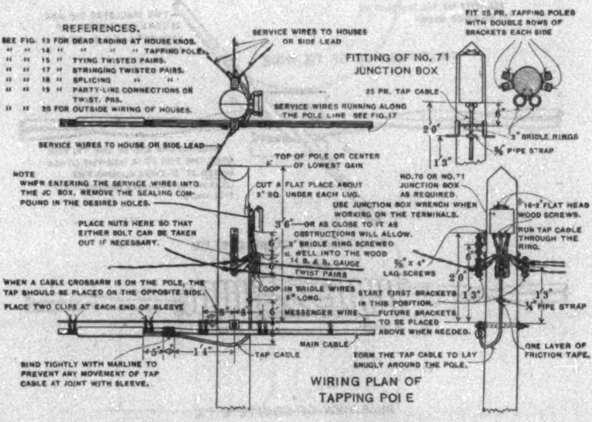

REFERENCES.
SEE FIG. 13 FOR DEAD ENDING AT HOUSE KNOB.
" " 14 " " " " TAPPING POLE.
" " 15 " TYING TWISTED PAIRS.
" " 17 " STRINGING TWISTED PAIRS.
" " 18 " SPLICING " "
" " 19 " PARTY-LINE CONNECTIONS ON TWIST. PRS.
" " 20 FOR OUTSIDE WIRING OF HOUSES.
SERVICE WIRES TO HOUSES OR SIDE LEAD
FITTING OF NO. 71 JUNCTION BOX
FIT 25 PR. TAPPING POLES WITH DOUBLE ROWS OF BRACKETS EACH SIDE
25 PR. TAP CABLE
SERVICE WIRES RUNNING ALONG THE POLE LINE SEE FIG.17
6"
2'0"
3" BRIDLE RINGS
⅜" PIPE STRAP
1'3"
SERVICE WIRES TO HOUSE OR SIDE LEAD
TOP OF POLE OR CENTER OF LOWEST GAIN
NOTE
WHEN ENTERING THE SERVICE WIRES INTO THE JC BOX, REMOVE THE SEALING COMPOUND IN THE DESIRED HOLES.
CUT A FLAT PLACE ABOUT 3" SQ. UNDER EACH LUG.
NO.70 OR NO.71 JUNCTION BOX AS REQUIRED.
USE JUNCTION BOX WRENCH WHEN WORKING ON THE TERMINALS.
#16-2" FLAT HEAD WOOD SCREWS.
PLACE NUTS HERE SO THAT EITHER BOLT CAN BE TAKEN OUT IF NECESSARY.
3'6"—OR AS CLOSE TO IT AS OBSTRUCTIONS WILL ALLOW.
RUN TAP CABLE THROUGH THE RING.
6"
3" BRIDLE RING SCREWED WELL INTO THE WOOD
14 B. & S. GAUGE
TWIST PAIRS
⅜" X 4" LAG SCREWS
6"
2'0"
WHEN A CABLE CROSSARM IS ON THE POLE, THE TAP SHOULD BE PLACED ON THE OPPOSITE SIDE.
LOOP IN BRIDLE WIRES 8" LONG.
START FIRST BRACKETS IN THIS POSITION.
1'3"
1'3"
¼" PIPE STRAP
PLACE TWO CLIPS AT EACH END OF SLEEVE
8"
8"
6"
MESSENGER WIRE
FUTURE BRACKETS TO BE PLACED ABOVE WHEN NEEDED.
MAIN CABLE
5"
1'4"
TAP CABLE
ONE LAYER OF FRICTION TAPE.
FORM THE TAP CABLE TO LAY SNUGLY AROUND THE POLE.
BIND TIGHTLY WITH MARLINE TO PREVENT ANY MOVEMENT OF TAP CABLE AT JOINT WITH SLEEVE.
WIRING PLAN OF TAPPING POLE

FIG. 15—Details of construction at branch terminal pole

There will, of course, be many streets and districts where for the present time aerial cable is not warranted. If these districts are in the neighborhood of an aerial cable base line, and the subscribers are not located more than 1000 feet away from the cable line, it is economy to connect them with twisted-pair wire strung on distributing brackets rather than to resort to the use of bare wire and cross-arms, where perhaps a large part of the arm capacity will lie idle for several years. This method of wiring is shown in Fig. 19. If the side streets are clear of trees and it appears probable that many of the circuits will be more than 1000 feet long, the distribution should be made by means of bare wire on cross-arms, as shown in Fig. 20. Generally speaking, the bare wire on these side lines should

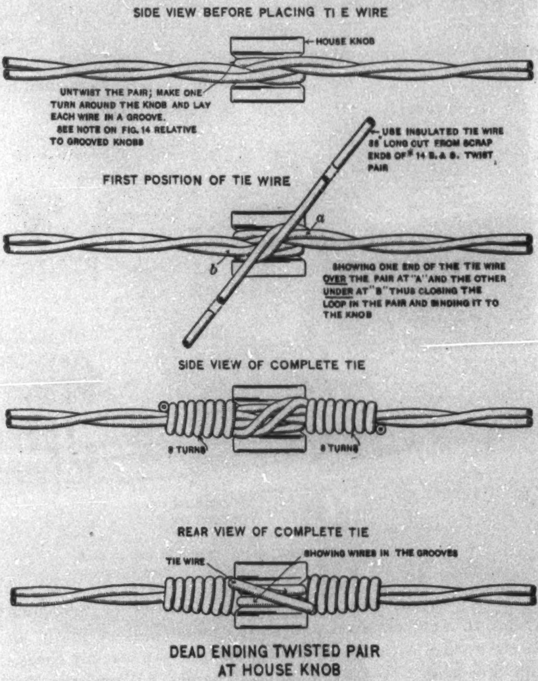

SIDE VIEW BEFORE PLACING TI E WIRE
HOUSE KNOB
UNTWIST THE PAIR; MAKE ONE TURN AROUND THE KNOB AND LAY EACH WIRE IN A GROOVE.
SEE NOTE ON FIG. 14 RELATIVE TO GROOVED KNOBS
USE INSULATED TIE WIRE 36" LONG CUT FROM SCRAP ENDS OF # 14 B. & S. TWIST PAIR
FIRST POSITION OF TIE WIRE
a
b
SHOWING ONE END OF THE TIE WIRE OVER THE PAIR AT "A" AND THE OTHER UNDER AT "B" THUS CLOSING THE LOOP IN THE PAIR AND BINDING IT TO THE KNOB
SIDE VIEW OF COMPLETE TIE
8 TURNS
8 TURNS
REAR VIEW OF COMPLETE TIE
TIE WIRE
SHOWING WIRES IN THE GROOVES
DEAD ENDING TWISTED PAIR
AT HOUSE KNOB

Fig. 16—Method of tying twisted-pair insulated wires to porcelain knobs

be of copper, for at the present time with so much sulphurous smoke in the atmosphere of our cities and towns, the life of iron wire is too short to warrant serious consideration. Copper wire smaller than No. 14 N. B. S or No.

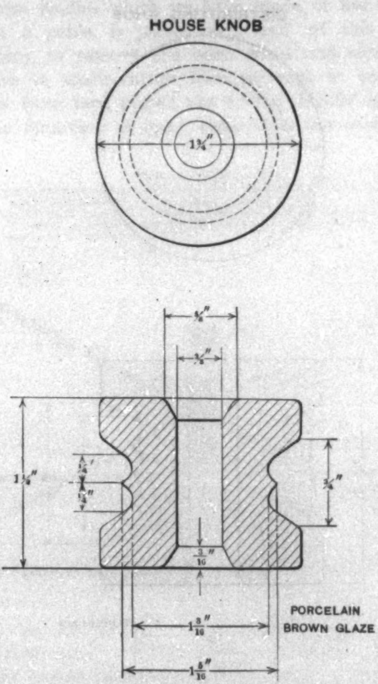


FIG. 17—Porcelain knob used for attaching twisted pair drop wires to houses

12 B. & S. gauge cannot safely be used in spans because of of its low tensile strength. This size of wire is not required for conductivity, since in the places where this wire is usually strung we would be satisfied with a cable conductor of 19 or 22 gauge. Here again it also seems possible to make considerable

saving by the use of copper-clad steel wire. A No. 14 B. & S. or No. 16 N. B. S. copper-clad wire is sufficiently strong mechanically and has a conductivity equivalent to a 19-gauge cable pair. This will reduce the first cost of line wire about one-half. The copper-clad wire will be just as durable as copper, and since its strength lies on the inside rather than in the hardened outside shell, it will be subject to a lesser number of breaks, and besides it can be taken down and used in other places. It is usually necessary to scrap copper wire when taken

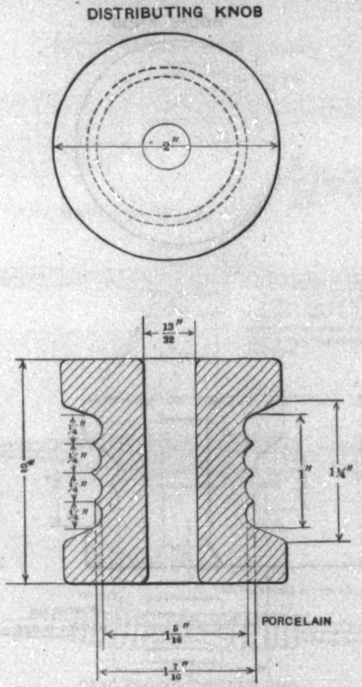
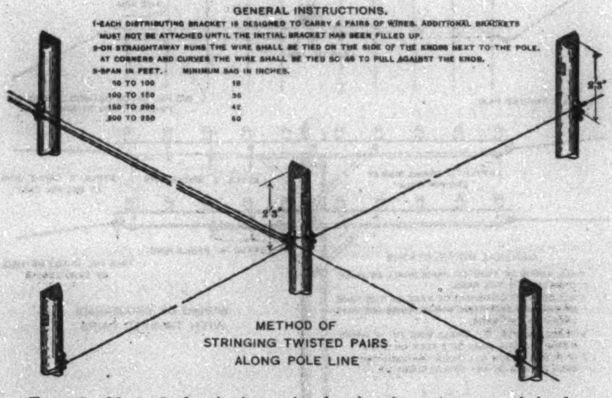


FIG. 18—Porcelain knob used for attaching twisted pair drop wires to poles

down, for as a rule it will not stand re-stringing in another location without causing much trouble from breaking, due to nicked and scratched spots.

When the open-wire subscribers' circuits fill several cross-arms, it is generally economical to replace them with a cable. From studies which we have made, it has been found that when a cable is placed on a lead of this character, it is economy to remove the open wires and cross-arms and return them to stock rather than attempt to use them for distribution from taps placed one to two blocks apart on the cable. The removing of open wires when the cable is placed, cleans up the line in good shape, makes it easy to maintain, and far more sightly to the public It would seem that the aerial cable system of distribution of telephone lines is the most ideal system now known for districts where for the present conduits are not justified. Practically all the large telephone companies have realized the economies to be obtained by its use, and during the last three years thousands of miles of this kind of cable distribution have been placed.



GENERAL INSTRUCTIONS.

1-EACH DISTRIBUTING BRACKET IS DESIGNED TO CARRY 4 PAIRS OF WIRES. ADDITIONAL BRACKETS MUST NOT BE ATTACHED UNTIL THE INITIAL BRACKET HAS BEEN FILLED UP.

2-ON STRAIGHTAWAY RUNS THE WIRE SHALL BE TIED ON THE SIDE OF THE KNOBS NEXT TO THE POLE. AT CORNERS AND CURVES THE WIRE SHALL BE TIED SO AS TO PULL AGAINST THE KNOB.

3-SPAN IN FEET.	MINIMUM SAG IN INCHES.
50 TO 100	18
100 TO 150	36
150 TO 200	42
200 TO 250	60

FIG. 19—Method of stringing twisted-pair wires along a pole lead

Since the wire plant requires the major portion of the money expended for a telephone system, and since there are so many varied and complex factors entering into its design, the greatest care should be given to its engineering. The most important problems in connection with the wire plant are:

1. The development plans which must be carefully worked out by the engineer so that not only the first cost of the plant will be a minimum, but so that the plant can take care of increases in business from time to time without unnecessarily large expenditures for redesign and reconstruction.

2. The transmission must be carefully studied so that there will be a good volume of talk between any two connected subscribers. The circuits, whether in cable or in open wire, should be graded and if necessary loaded, so that while the transmission is sufficiently good, it will not be given over unnecessarily expensive trunk lines.

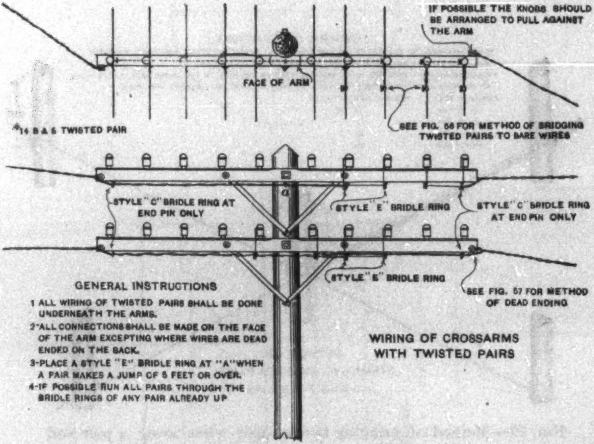

IF POSSIBLE THE KNOBS SHOULD BE ARRANGED TO PULL AGAINST THE ARM
FACE OF ARM
#14 B & S TWISTED PAIR
SEE FIG. 56 FOR METHOD OF BRIDGING TWISTED PAIRS TO BARE WIRES
a
STYLE "C" BRIDLE RING AT END PIN ONLY
STYLE "E" BRIDLE RING
STYLE "C" BRIDLE RING AT END PIN ONLY
STYLE "E" BRIDLE RING
SEE FIG. 57 FOR METHOD OF DEAD ENDING
GENERAL INSTRUCTIONS
1 ALL WIRING OF TWISTED PAIRS SHALL BE DONE UNDERNEATH THE ARMS.
2-ALL CONNECTIONS SHALL BE MADE ON THE FACE OF THE ARM EXCEPTING WHERE WIRES ARE DEAD ENDED ON THE BACK.
3-PLACE A STYLE "E" BRIDLE RING AT "A" WHEN A PAIR MAKES A JUMP OF 5 FEET OR OVER.
4-IF POSSIBLE RUN ALL PAIRS THROUGH THE BRIDLE RINGS OF ANY PAIR ALREADY UP
WIRING OF CROSSARMS WITH TWISTED PAIRS

FIG. 20—Distribution of subscriber's lines by means of open wire on cross-arms Twisted-pair drops to subscriber's premises

3. The underground system must be extended as rapidly as it is economical to do so, and direct terminal or interior block connections made with the maximum number of subscribers.

4. In the outlying districts where pole lines will still be

resorted to, every effort must be made so to design and construct these lines as to have them of low first cost and annual charges. They must be but slightly affected by the elements, and free from interference from electric light and power circuits. These aerial systems must be made sightly to avoid the criticisms of the public.

5. The engineer must constantly seek for new and improved types of material and construction methods to be used in the wire plant so that the first cost and maintenance can be reduced.

DISCUSSION ON "THE TELEPHONE WIRE PLANT" AT NEW YORK, APRIL 26, 1907.

John J. Carty: From the paper it is evident that the telephone wire plant consists of the conducting wires joining points distant from each other, and a large amount of auxiliary apparatus pertaining thereto. This distinguishes the telephone wire plant from that part of the plant which is composed of switchboards, telephones, transmitters, and the various classes of apparatus associated therewith.

The paper does well to call attention to the very great magnitude of the telephone wire plant as compared to the switchboard plant. The switchboard apparatus, all being assembled at the central office, can readily be viewed as a whole, and presents a commanding appearance. Very likely for this reason in the usual discussion of switchboards and switchboard apparatus those factors have been brought into undue prominence as compared with those parts of the plant which have been discussed to-night. The switchboard has too long held the center of the stage, and it is high time that attention has been directed to some of the numerous other features, aside from the switchboard, which are necessary for a complete telephone system.

The telephone wire plant of the city of New York and the suburban territory tributary to it consists in round numbers of one million miles of copper wire. Most of this copper wire is enclosed in lead-covered cables. The superficial area of the lead pipes covering a particular one of these cables amounts to 7.6 acres. The superficial area of the lead pipes covering all of the cables in this system of one million miles of wire amounts to 190 acres. All of this lead pipe is needed to protect from water and moisture the delicate paper-covered wires within, as a puncture in one of these pipes no larger than a pin-hole will admit moisture, which sooner or later causes a fault that produces an interruption of the service of one or of all the circuits within the cable. All of these 190 acres of lead pipe must therefore be maintained free from punctures even as small as that which would be produced by a pin, so that in the manufacture and laying and maintaining of this part of the telephone wire plant very important and serious problems are presented.

A few words concerning the development of this type of lead-covered cable may be of interest as bearing upon the subject under discussion. In the first telephone installations the wires, as a rule, were overhead and composed of iron, following the standard telegraph practice of the time. Soon it became necessary to extend telephone wires across rivers, and here for the first time telephone cables were used, the gutta percha or rubber-covered cables employed by the telegraph companies being imported into the telephone service for the purpose. As the number of wires increased, rubber-covered wires in cables were used to run upon poles and house-tops.

Some use was also made of overhead cables composed of cotton saturated with beeswax and protected with rubber tape and braid. As might be expected in the light of our present knowledge, these cotton and beeswax cables failed. This failure, taken together with the bad experience obtained with paraffin-covered cotton office wires, led to the conclusion that cotton was a bad insulator and for some time, where cables were employed, rubber was the material used.

Owing to the high specific inductive capacity of rubber, the transmission obtained through rubber cables was extremely defective and the cross-talk was almost intolerable.

Experiments were also made with rubber-covered wires at an early date, laid in underground ducts. These wires were unprotected by lead pipe, and besides being open to the before mentioned objections to the use of rubber cable, were especially subject to decay in many places underground.

All of these experiences led to a search for something better than rubber. Foremost among those who worked upon this problem was Mr. William R. Patterson, whose scientific investigations and remarkable practical skill brought forth a cable consisting of cotton and paraffin, in this respect resembling very much the cotton and beeswax cable which had been the cause of so much disastrous experience. It was difficult to convince anyone that cotton and wax could be a good insulator, but it was shown that perfectly dry cotton was an excellent insulator and that the former failures were due to the fact that, owing to its hygroscopic nature, cotton had absorbed moisture from the atmosphere and in the process of manufacture, and thus had its insulation destroyed. It was demonstrated that if the cotton core of the cable were throughly dried in an oven and then quickly hauled into a lead pipe and sealed up at the ends, that insulation as high as one thousand megohms or more per mile might be obtained, and that this high insulation would persist as long as moisture was kept from the core. The introduction of such a cable involved an entirely new state of the art and required that all those engaged in telephone construction should reform their ideas in the light of the new knowledge. After much agitation and discussion, and after a vigorous campaign of education, the superiority of the fibre cable, properly made and installed and maintained, was demonstrated. From that time the use of rubber cable began to decrease.

After much experience, it was found that the filling of wax might be omitted from the cable and yet the moisture could be kept out. This resulted in dry-core cotton cable, which had the advantage of much lower capacity than the filled cable and was not so much affected by heat as was the cable containing wax. The step from the use of dry cotton to the use of paper was a very important one and accomplished much in the way of economy.

The underground telephone cable of to-day is composed of copper wires covered with paper, all enclosed in a hermetically sealed lead pipe. This type of cable has persisted so long and seems to answer its purpose so well, that telephone engineers are fairly well content with it, and are no longer agitated by those serious questions which I have just discussed.

The tendency in cable construction and in telephone line construction generally has been to drive rubber insulation out of the field which it formerly dominated. Its use is now restricted to distributing wires, inside wiring, and certain special switchboard wiring. While the use of this rubber insulation has relatively decreased in the absolute amounts used, there has been a tremendous increase in the mileage employed. So important still is the use of this rubber wire that the question of its durability and cheapness is one of very great concern, and I am glad to see that in the paper just read there are some valuable data concerning the durability of rubber wire under certain conditions. Reliable data on this subject are much needed.

The open wires used in the first telephone lines were usually made of iron, and, as a rule, especially when employed in lines of any great length, they gave impaired service. The reasons for this are of course now well understood, but at the time of which I speak not much was known concerning the laws of transmission, nor of the electrical and magnetic properties of iron. There was a long period of groping in the dark. Where long-distance wires—at that time forty or fifty miles was long distance—were used, imperfect results were obtained, and in some cases it seemed that by using larger iron wires matters were made worse. During all of this period of fumbling and groping, there was one engineer with clear vision who perceived that if copper could be obtained with suitable mechanical qualities, it would be an excellent material for telephone lines. He directed his attention to this subject and produced hard-drawn copper wire in suitable form for telephone lines. I refer to Thomas B. Doolittle, who was the first one to use hard-drawn copper wire as the material for telephone lines. Hard-drawn copper wire was thus used by him at an early date at Ansonia, Conn. The results obtained were satisfactory, and, after a number of years had elapsed, a practical demonstration of the value of hard-drawn copper wire for long-distance lines was made by stringing a circuit extending from Boston to New York. The success of this circuit, using hard-drawn copper wire, demonstrated the feasibility of long-distance telephony. Here again the art of stringing wires had to be reformed. Linemen, foremen, engineers, and managers had to be taught how to handle the new material, the factories had to be instructed in its making, and even a new joint had to be perfected. The size of wire to be used had to be determined, and this was found out when the New York-Philadelphia long-distance line was established, upon which wires of various sizes were strung.

Those which were mechanically weak were eliminated and many valuable data were obtained. Since those times, hard-drawn copper wire has been found to be the only material suitable for long-distance lines. Compound wires of various sorts have been suggested from time to time, but invariably they have been found unsatisfactory for long-distance transmission. Whatever use they have must be for local lines and the precise function of this bimetallic wire in such lines is yet to be generally agreed upon.

While much has already been accomplished in the perfection of the telephone wire plant, much still remains to be done; and to make our record of future achievement as worthy as that which has already been accomplished we must constantly direct our efforts not only along broad and comprehensive lines, but we must also pay strict regard to each and every one of the thousands of small pieces of apparatus, many of which are dealt with in the paper, and all of which go to make up the sum total of the telephone wire plant.

Hammond V. Hayes: The methods of telephone plant development which Mr. Grace has described represent those which we are now employing and which have been employed by the Bell engineers for a number of years past. Practically every city and town in this country has been studied, and all new work is carried out on well-considered lines as formulated by development plans of this character.

The development plan is simply a forecast, what someone, I think Mr. Carty, has called a guess based on scientific or engineering principles as to what may be expected for the future of the telephone business in each particular locality. So difficult is this forecast of the future, and so inadequate are any rules or formulas, that it has been our custom to employ for this work, as far as has been possible, a group of young men who have gained special training by the varied experience derived from the preparation of plans of this character for cities and towns scattered throughout the country. We find that in many parts of the country the optimism of local men is such as unduly to distort their judgment as to the future size and importance of their own towns; and, occasionally, although rarely, there is such insufficient appreciation of telephone possibilities that there is a tendency to create plants of insufficient size. Even engineers that are detailed for this work have methods of estimating and checking their work which cannot be definitely formulated. In fact, it is their judgment based on wide experience which prevails. I have no doubt that in very many cases as good or better estimates for the future can be made by men of good judgment and good sense without resorting wittingly to the elaborate method such as we describe; I say this but to emphasize the fact that in this as in every other engineering problem it is good judgment based on ample and proper premises which is of importance.

Mr. Grace has talked and spoken of an "all-cable" plant. I want to emphasize that the all-cable plant as described refers simply to the distribution of lines within a city. All the planning done in every city and town in the country is to arrange the plant so that the distribution of the wires to the sub-stations may be satisfactory and that it may be possible that each sub-station in each town will be capable of talking with every other sub-station in other towns. This placing of lines in cables cannot be applied to the wires used for long-distance circuits to any great extent, for the reason that the cables tend to cut down the efficiency of service; what must be done is to keep the wire plant of the system not only the best possible for maintenance reasons, but to arrange it so that it is capable of rendering possible communication over the widest possible range of territory.

I am much interested in some of the mechanical features of the plans that Mr. Grace has shown us, and I hope that I may take the liberty of speaking of the cable-box. Mr. Grace has with great modesty said but little about it. This box is his own work; he designed it and perfected it, and I hope that it will be used very generally in the future throughout the United States.

I would like to say one word more about the question of steel and copper wire, following substantially the same thought that was in Mr. Carty's mind. Wire of this character was used some years ago in this country and has been on the market in Europe for many years. I am very glad indeed that the experiments with this wire are being carried out by Mr. Grace. I hope that he will continue the experiments, and will tell us at some later time what his success is and if such a wire offers an additional means of line distribution. I feel, however, that the wire plant is so important a feature of the telephone system that it would be well to go slowly and consider a material of this character as an experiment until such time as it has been more thoroughly tried out.

G. M. Yorke: The system described by Mr. Grace contains a minimum amount of open wire. As Mr. Hayes has said, this system is mainly used for connecting the subscribers' stations with the nearest central office. This portion of the plant has to be made compact and sightly. But a large percentage of its use is merely for communications between stations only a very few miles apart. Now, when we consider that other very important portion of the telephone plant, used for connecting central offices together many miles apart, hundreds of miles apart, we see that such an extensive use of cable is quite impossible. The reason for this is that cable circuits have always been very inefficient in transmitting speech. This inefficiency still exists in spite of the improvements in cable manufacture that have been touched upon and also in spite of other general improvements in the art. As an example of the inefficiency of cable circuits, take the type of circuit used for the longest distances in this country. These circuits are about fifty times as efficient as the form of cable circuit described by Mr. Grace, and used so largely for subscribers' lines. In other words, one of the regular lines from New York to Chicago talks as well in volume and in quality as a cable circuit only twenty miles long of the sort described by Mr. Grace. A further point is that if we connect only ten miles of such cable to this long open wire circuit, it is necessary, in order to keep the transmission efficiency at the same point of loudness and quality, practically to double the weight of copper in the long line circuit. Of course this is an extreme illustration. In view of this relative inefficiency of cable circuits, we are not going to speak right away of an all-cable long-distance plant. It is necessary to bring the open wires as near to the center of the terminal cities as is practicable and to keep all cable out of intermediate cities if we can. This becomes more and more necessary in view of the increasing amount of cable that it is necessary to use in subscribers' lines. I simply want to point out that the open wire is not to be abandoned just because it is unsightly. We are going to keep it if we are going to keep long-distance telephone service.

F. L. Gilman: As has been said several times, a material advance has been made in the art of cable manufacture, and the present paper-insulated cable has been used in its present form for a good while with satisfaction. One great effort in recent years has been in the direction of getting more wires into a given amount of space without increasing too much those electrical characteristics of the cable which are harmful to transmission, and without using sizes of wire that cannot be handled easily.

Mr. Grace has spoken of the braided rubber-covered wire used between the cable terminals and the subscribers' stations. Perhaps if I outline briefly the conditions which obtain, the problem of this rubber-covered wire will be realized more clearly. In telephone lines there is constantly a difference of potential existing between the two sides of the line and between one side of the line and ground; and throughout its entire length, in the kind of distribution of which Mr. Grace has been speaking, the line is composed of twisted wire. This is true of the rubber-covered wire as well as of the rest of line. The two wires are twisted together to keep outside disturbances from affecting the telephone transmission. Furthermore, the resistance of the part of the circuit including the rubber-covered wire has certain limitations. Then again, as can be seen from the pictures, this part of the plant runs anywhere and everywhere; it is on walls and fences; it is generally outdoors where it is exposed to sleet and rain; in the summer-time it is subjected to excessive heat, and in the winter-time to extreme cold. In other words, this wire is everywhere in the system and in nearly every telephone line in the large cities.

Now, if the wire is not in first class condition and has not first-class insulation there are a number of different troubles that exist. In the first place, there is a waste of current and the possibility of electrolysis. Then there is sensitive apparatus in the central office which will be affected. More important than these is the transmission which is also in jeopardy. If there is a leak on one wire of the pair, the line will be noisy; or if there is a leak between the two wires of a pair, reduced transmission will result because of the short-circuit. Another reason for first-class insulation is the fact that this braided rubber-covered wire is fairly expensive to start with, and the running of it is also expensive, so the life has to be long in order to make such construction economical. Furthermore, because of the moving of subscribers, this wire may have to stand taking down and putting up again.

What I want to bring out clearly is the fact that it is requisite that the wire used for this purpose shall be of first-class quality and maintain its insulation. Of course we are more or less familiar with braided rubber-covered wire, but perhaps we have not all realized just what the vital point is. The rubber compound itself will not last unless it is properly protected. The usual method of protecting the braid is a cotton braid, but that will not stand the heat and rain of summer unless it is properly protected, so the whole gist of the matter is the protection of the braid—some protection that will not run off in summer and will not crack in winter.

Kempster B. Miller: I wish that the Institute might have more telephone papers of this kind, wherein plants in different parts of the country are described not only in general terms but with a considerable amount of detail. Such description of practices in different parts of the country, and a frank discussion of them, are just as necessary and desirable in telephony as in any of the other arts, and I think perhaps more necessary, because they have been less common.

It is often interesting to watch the tendency of growth in the development of any art. From what has been said to-night, it is evident that there is a tendency to decrease gradually the use of bare wire in local telephone plants—I am speaking of the local plant as distinguished from the long-distance plant. There are some who contend that there should be absolutely no bare wire in a local telephone plant, and several plants of considerable magnitude have been constructed in which I understand there is not a foot of bare wire. The practice that Mr. Grace has outlined stops just short of this extreme, and it seems to me that it stops in just the right place. To say that there shall be absolutely no bare wire in the plant, simply for the purpose of being able to boast that there is none, is in the nature of riding a hobby rather than of good engineering.

Another tendency that has been brought out, not only by Mr. Grace but by Mr. Carty and others, is the diminishing use of rubber-insulated wire in telephone plants. Not long ago we did put a little rubber wire into almost every cable; that is, at the outer end of the cables. The practice that Mr. Grace describes does away with this in a large measure, certainly on all the small cables. He terminates the paper cable directly in a terminal sealed with an insulating compound so that there is no rubber-covered wire in that part of the plant. This means that the only rubber-covered wire is in the drop wires and in the house wires.

Perhaps after hearing of the beauties of the paper cable as outlined by Mr. Carty, people in other arts than telephony may be so impressed that they will adopt paper cable where it may be dangerous to do so. The paper cable is used in telephony because there is no other form of cable that we know of to take its place. Whatever may be said of paper cable, it is subject to one very serious drawback—any slight puncture of the sheath is liable to put all the wires out of business. While such troubles as these are readily repaired, yet they are very apt to occur. In other systems of communication where the high frequencies of telephony are not employed, it is feasible to use rubber, or gutta-percha, insulated wires, and their reliability is infinitely greater than that of paper-covered wire. For this reason where the cable is difficult of access, as in submarine work, or where reliability is of paramount importance, as in the fire-alarm telegraph, the paper cable has little place.

A paper presented at the 218th Meeting of the American Institute of Electrical Engineers New York, April 26, 1907.

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LIGHT FROM GASEOUS CONDUCTORS WITHIN GLASS TUBES—THE MOORE LIGHT

BY D. MCFARLAN MOORE

Energy can be conveniently classified under six general heads: mechanical motion, sound, heat, electricity, light, chemism.

The term "light" should be used, not as the name of an effect on the eye, but to designate one of the great divisions of all energy. Each division always contains a percentage of all the other divisions, and the less this percentage the purer is the division sought after. The less heat, etc., light contains the more efficient we call it.. Science should know how efficiently to change or convert any one of these divisions into any other one. For example, we do know how efficiently to change electricity into mechanical motion; namely, by the use of an electric motor, but we are ignorant concerning many of the other 29 combinations, which indicates that there remains plenty of scientific work to be done by future generations.

Since all energy is really the same thing, we should become proficient in magnifying or suppressing, at will, any particular division or divisions, corresponding with rate of vibrations which we have settled upon and named largely because they affect in a distinctive manner the different organs of our bodies.

Some years have passed since I first realized that there then existed no form of artificial light that could truthfully be said to imitate daylight. Believing unalterably that such a light was to be the next logical step of great importance in artificial illumination, I commenced an investigation that still continues.

To duplicate daylight closely, three premises were soon determined upon which have never been abandoned:

1. Large light source, the practical solution being a long glass tube emitting light.

2. Use electricity flowing through a gaseous-conductor, not a solid conductor.

3. Perfect imitation of daylight color values.

Immediately on beginning investigation on these premises, the gaseous-conductor became the factor of greatest importance. The life of the first lamps or tubes constructed was extremely short, since, as then expressed, "the vacuum deteriorated" Up to date, four methods have been developed and used and thousands of experiments have been made concerning the replenishing of the gas and thereby overcoming this vital difficulty of the gaseous-conductor becoming non-conducting, due to the peculiar chemical reaction that must occur when electricity passes from a solid conductor to a gaseous-conductor. These methods are as follows:

1. By obtaining a cycle of events through catalytic action. The intensity of light possible was found to be very low.

2. Obtaining a cycle by evaporation and condensation. Probably mercury is the only element that can ever be used in this way in glass tubes.

3. By re-supplying the necessary gases automatically by the action of heat on suitable substances.

4. By automatically feeding gas to the tube when needed, which is the method used at the present time.

Inventing intricate theories for explaining vacuum-tube phenomena was easy compared with furnishing a merchant a practical tube light to sell his goods under. For some years past there has existed a great mass of theoretical literature on gaseous conduction etc., but practically none that dealt with watts and hefners under commercial conditions. The old "pith-ball" phenomena of elementary physics is still a good working hypothesis for explaining the passage of electricity through gases, especially at less than atmospheric pressures. It is apparent that movements of the almost infinitely small "pith-balls" or ions is regulated largely by the potential and degree of vacuum. A collision of two moving bodies results in heat. The general law of all light sources applies also to the vacuum-tube light: namely, the higher the temperature the greater the efficiency. The absolute temperature of the individual particles of matter within the tube after collision is greater than that of any other temperature on earth. But the quantity of heat of each of these ultra incandescent, though infinitesimal, bodies, is so small that there results that which at first would seem paradoxical: namely, the "coldest" source of light. In this expression we crudely refer to the external temperature of the entire tube. Some gases are easily ionized and conduct well, yet give practically no light, which may indicate that their chemical constituency and therefore their emissivity is not suitable for light production.

In two previous papers which I had the honor to present to this Institute*, certain statements were made as to what would probably be the system of illumination which would finally, in great measure, supplant the systems then and now existing. The subject of improved artificial lighting methods is one of the greatest economic problems of the day. Time and space will not permit in this paper a historical review either of these investigations or of the art as a whole. The way has been long and strenuous, but always interesting. Careless criticism has been plentiful and professional support rare. The system herein described has become known as the "Moore Light" and therefore I trust you will pardon, on simply the ground of expediency and brevity, my reference also to it by that name, there being no alternative.

The present system has passed the experimental stage. It is a result of twelve years of experimenting, but its advance from year to year has always been steady. It is now fitting that an authoritative technical record be made of the essential facts at present connected with it. At the outset I venture to assert that if one thoroughly versed in the art of illumination should formulate entirely on theoretical lines complete, ideal specifications for an artificial illuminating system, that he would unconsciously describe he essential features of the lighting system described in this paper. It contains no "make and break" apparatus whatever.

For many years all scientists have agreed that a vacuum-tube light would be right theoretically: commercial men who have had their electric lighting bills reduced now know of its practical value.

The illumination of this assembly room, Fig. 1, at the present moment by a so-called Moore vacuum tube, greatly facilitates making clear not only its mechanical construction, but also its many other salient advantages and characteristics. The electrical energy is obtained from the alternating-current street mains.

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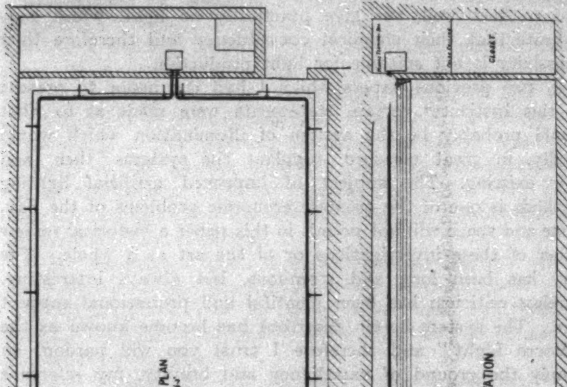
* "A New Method for the Control of Electric Energy," September 20, 1893; "Recent Developments in Vacuum Tube Lighting," April 22, 1898.

It will be noted that the light emanates with absolute uniformity from the entire area of a single, continuous glass tube 1.75 in. in diameter in the form of a large rectangle 62 ft. by 25 ft. which is supported on the cove designed to conceal the incandescent lamps. The glass tube is 13 in. from the ceiling and 16 ft. from the floor, as shown by Fig. 2.



Figs. 1 and 2

It is supported by plain brass rings $1\frac{7}{8}$ in, in diameter attached to small procelain insulators inserted in the ends of brass fixture tubing which of course contains no wires.

The two ends of this continuous tube at the center of the rear side of the rectangle approach within such a short distance of each other that the gap is scarcely discernible from the floor. They then extend horizontally through the wall and into a rigid steel terminal-box located on the wall of the closet at the rear of the hall. This terminal-box contains all the necessary electrical apparatus and corresponds in form and size with that shown in Fig. 3. It is fed by 60-cycle alternating current at 220 volts. Besides the two carbon electrodes of the tube, the terminal-box contains a step-up transformer and a small specially designed valve with its solenoid, which represents an entirely new departure in vacuum tube lighting and also

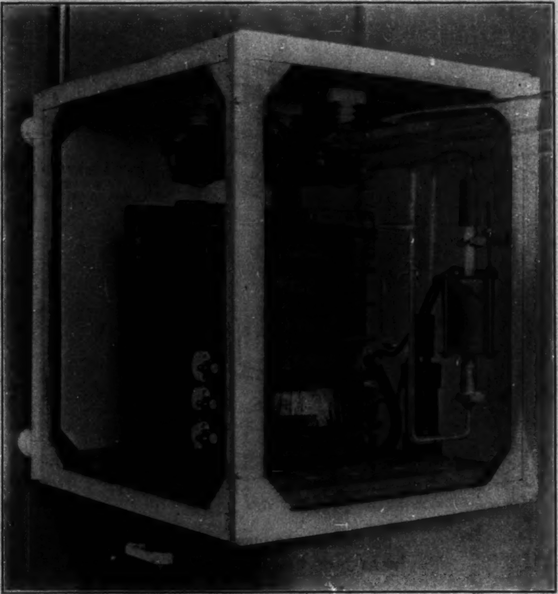


FIG. 3—Interior of terminal box

one that is vital to its success. The electrical circuits from this apparatus are extremely simple and are shown in Fig. 4. There is no distributed or high-potential wiring. The high-potential terminals of the transformer within the terminal-box are only two or three inches in length and are attached directly to the electrodes within the box. All the high-potential wires, therefore, always remain within the box which has a wire seal placed upon it. A hand can be placed on each of the glass tubes near where they emerge from the two holes in the side of the box, but the glass tubes insulate the gaseous-conductor within them so well that no shock can be felt.

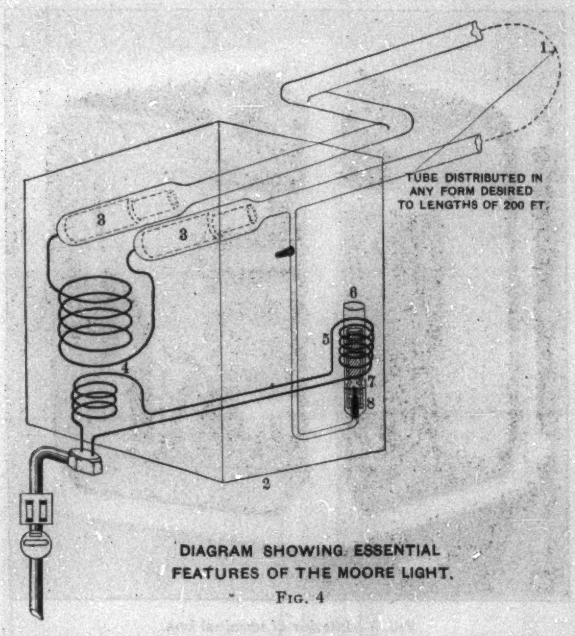


DIAGRAM SHOWING ESSENTIAL FEATURES OF THE MOORE LIGHT.

Fig. 4

Since the feeder-valve operated by the solenoid just mentioned is an essential feature of this system, a description of its operation will be interesting. Any vacuum tube when commercially luminous will, in a few minutes, seriously alter the degree of its vacuum unless special provision be made to replenish its gaseous-conductor. Due to the flow of current, a portion of the residual gas within the tube is absorbed; that is, changed to a solid form, and thereby the degree of vacuum in the tube becomes higher.

This higher degree of vacuum so increases the resistance of the tube that at first the light simply becomes unsteady but rapidly changes to a condition of violent spasmodic flickering, which soon entirely ceases and the tube gives no light whatever. The light has actually died for want of air. This simple fact was not recognized for many years by prominent investigators in this line of phenomena. The problem, therefore, was to devise thoroughly practical means for replenishing the gaseous-conductor of a vacuum tube. This is the function of the feeder-valve which permits air or other gas to enter the tube only when it is needed and in such a manner that it is entirely automatic. A piece of $\frac{7}{8}$ in. glass tubing is supported vertically, see Fig. 5, its bottom end is contracted into a $\frac{3}{8}$ in. glass tube which extends

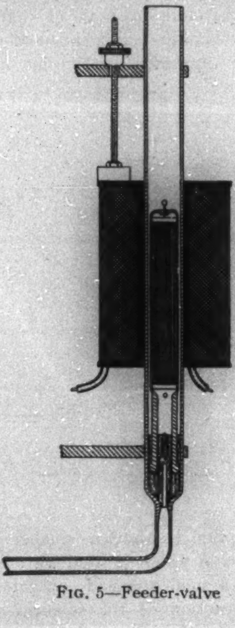


FIG. 5—Feeder-valve

to the main lighting tube. At the point of contraction at the bottom of the ⅞ in. tube there is sealed by means of cement a ¼ in. carbon plug, the porosity of which is not great enough to allow mercury to percolate through it but which will permit gases easily to pass, due to the high vacuum of the lighting tube connected to the lower end of the plug, and approximately atmospheric pressure above it. This carbon plug is normally completely covered with what would correspond to about a thimbleful of mercury which simply seals the pores of the carbon plug, and therefore has nothing whatever to do with the conducting properties of the gas in the main tube which produces the light. Partly immersed in the mercury and concentric with the carbon plug, is another smaller and movable glass tube, the upper end of which is filled with soft iron wire, which acts as the core of a small solenoid connected in series with the transformer. The action of the solenoid is to lift the concentric glass tube partly out of the mercury, the surface of which falls and thereby causes the minute tip of the conical shaped carbon plug to be slightly exposed for a second or two, and an extremely small quantity of air or other gas filters through it and then finds its way into the vacuum tube proper. In normal operation, most of the tubes expose this carbon tip for about one second every minute. Therefore, this system, broadly speaking, consists in continuously burning air electrically.

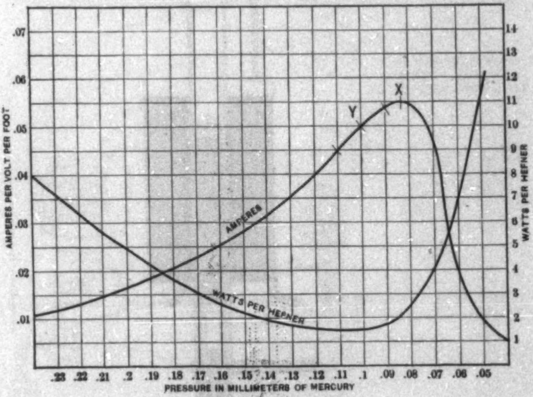


FIG. 6.

Fig. 6 will explain the theory of this action still more clearly. This curve shows the relation between conductivity and degree of vacuum. Of course there must be a critical degree of vacuum at which the conductivity is a maximum; this point corresponds to *X*. By means of the adjusting screw at the top of the solenoid the degree of vacuum is kept normally at a lower vacuum corresponding with *Y*, therefore as the electricity uses up the gaseous-conductor, the vacuum of course becomes higher, the conductivity better, and a greater current flows through the solenoid causing it to lift the displacer and expose the carbon tip above the surface of the mercury. In viewing its action, one

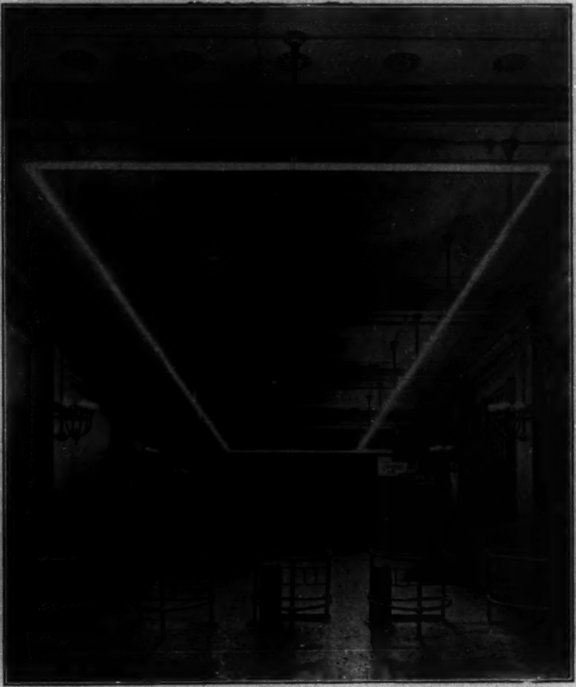


Fig. 7—Lobby of a theatre

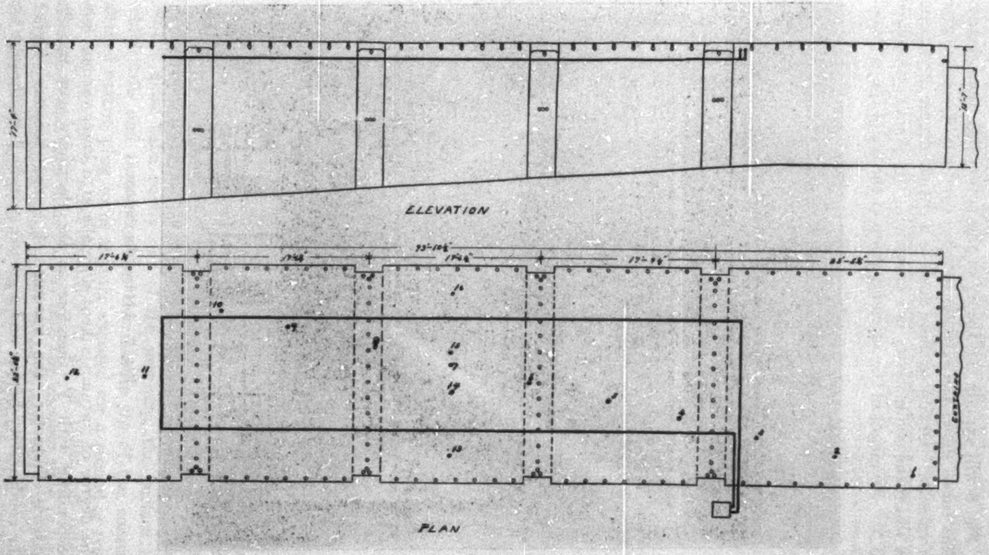

ELEVATION
PLAN

FIG. 8

is vividly reminded of a mud-turtle taking a breath of air on a mill-pond. As others have expressed it, this apparatus actually breathes. Immediately upon the air being admitted the vacuum falls, its resistance increases, and the current through it decreases as does also the current from the mains; therefore, the feeder magnet weakens and the displacer falls, thereby shutting off the air or gas inlet. This cycle is repeated about once a minute throughout the life of the tube, which is indefinitely long. Of course when the tube is not in service there is no leakage of air or other gas through the mercury covering the plug.

The following comparative illumination tests were made between the Moore tube located in the lobby of a large theatre (Fig. 7) and the incandescent lamps formerly used to light the same area

ILLUMINATION MEASUREMENTS IN HEFNER FEET IN THE LOBBY OF A THEATRE

Station	Moore Tube	Incandescent System
1	0.795	1.05
2	2.33	1.05
3	6.48	1.27
4	4.38	1.25
5	3.48	1.25
6	3.81	1.34
7	3.20	1.05
8	3.30	1.34
9	2.86	1.02
10	2.73	0.88
11	2.20	0.74
12	1.19	0.52
13	3.39	1.14
14	3.47	1.14
15	2.96	1.25
16	3.30	1.31
Mean illumination (average hefner-feet of 16 stations)	3.12	1.09
Average variation from mean	27%	16%
" volts	222 a.c.	115 d.c.
Amperes	21	51.75
Watts total	3075	5470
Power-factor	66	——
Area square feet	2110	2110
Watts per square feet	1.46	2.82
Illuminating efficiency $\frac{\text{Mean hefner-foot x area}}{\text{watts}}$	2.15	0.39

Therefore the tube system has 5.1 times the illuminating efficiency of the incandescent lamp system under the same local conditions. The useful illumination has been increased 450%, yet the current consumption is reduced 45%.

Although there are many factors which it is necessary not to lose sight of in determining the true value of any form of illuminant, nevertheless the sine qua non is the matter of efficiency. Does this apparatus produce more light for a given expenditure of energy than the other forms of illuminants with which it must naturally compete, is a question of vital importance?

A new and excellent type of portable illuminometer recently developed by Mr. Marshall was used to make these illumination measurements. At all stations it was placed 32 in. from the floor, although the floor of the lobby slopes towards the entrance end.

Fig. 8 shows a plan and elevation of this lobby. The tube is not provided with a reflector of any kind and therefore the ceiling was much brighter than when the incandescent lamps were used, most of which were located directly on the ceiling. The walls and ceiling are covered with a buff-colored paint. The tube operated directly from the street mains, 220 volts, 60 cycles, single phase.

If this tube had been longer its efficiency would have been still better, and by equipping it with a simple white reflecting enamel on the exterior of its upper half it would have had the benefit of a reflecting surface like most other forms of light in normal operation. Measurements of tubes so equipped show an efficiency corresponding to less than one watt per hefner and therefore approaching the theoretical limit for a light of such a commercially good spectrum.

The entire basement floor of a department store, which is solely lighted by four tubes each about 200 feet in length, is shown in Fig. 9. This basement was formerly lighted with enclosed alternating-current, 6-ampere, 60-cycle arc lamps. The goods are generally displayed on tables and shelves on the side walls, and the plane of measurement was chosen at the average height of the tables; that is, 36 in. from the floor.

The ceiling is 10 ft., 3 in. high and coated with gray paint. "B" tube is 199 ft. long, operating directly from the 60-cycle street mains; that is, there are no auxiliary devices to be taken into account as with some other forms of light. The center of the tube is 8 ft., 9 in. above the floor and the center of the arc lamp 8 ft., 6 in. above the floor. It was noted that various articles are suspended from the ceiling in this department, and that with the tube light the ceilings and walls were well illuminated, while with the arc lamps, due to their reflecting shades, the ceilings and walls were very dark.

The following comparative illumination tests were made between tube " B " when fed with pure nitrogen and therefore giving a yellow light, and the nine arc lamps provided with 15-in. white opalescent reflector shades formerly used to illuminate the same area.

ILLUMINATION MEASUREMENTS UNDER TUBE " B," DEPARTMENT STORE

Station	Moore Tube	Arc Lamp System
Vert. 1	2.84	1.30
2	1.76	1.14
3	4.66	1.25
4	2.02	0.68
5	2.84	0.59
6	3.75	0.75
7	1.34	0.45
8	1.91	0.68
Vert. 9	1.09	0.79
10	4.30	3.30
11	2.24	2.80
12	1.71	1.06
13	2.64	1.72
14	2.16	1.31
15	3.73	1.08
16	2.14	1.33
17	2.02	0.45
18	2.24	1.02
19	2.24	1.42
20	1.82	0.73
21	2.56	0.82
22	5.05	0.79
Mean illumination (average hefner-feet of 22 stations)	2.6	1.16
Average variation from mean	31.8%	40.4%
" volts	230	122
Amperes	24	53.1
Watts total	3500	4500
Power-factor	62.5%	70
Area square feet	3753	3753
Watts per square feet	0.93	1.2
Illuminating efficiency $\frac{\text{Mean hefner-foot x area}}{\text{watts}}$	2.79	0.967

Therefore the tube system with yellow light has 2.9 times the illuminating efficiency of the enclosed arc-lamp system under the same local conditions.

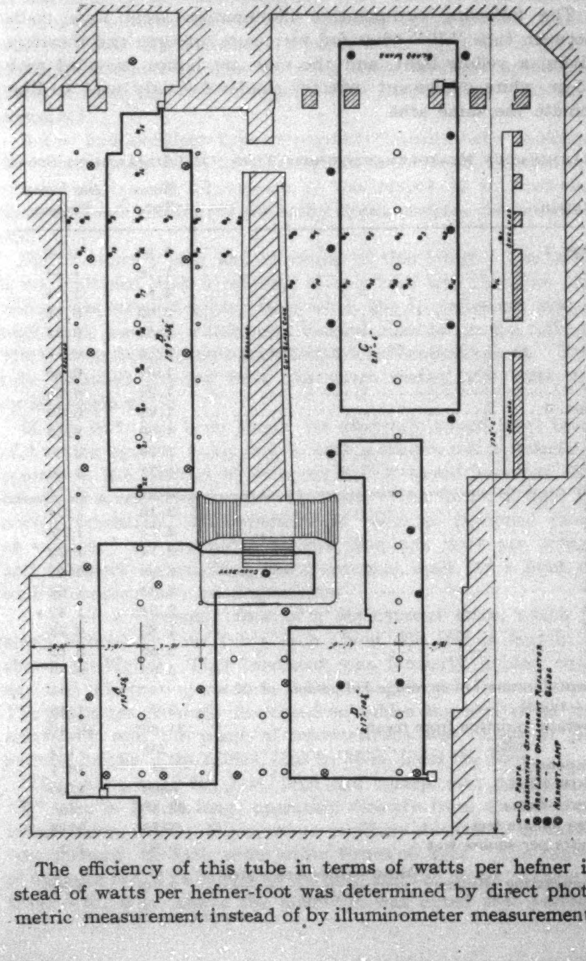

A
B
C
D
Posts
Observation Station
Arc Lamps Opalescent Reflector
Nernst. Lamp

FIG. 9

The efficiency of this tube in terms of watts per hefner instead of watts per hefner-foot was determined by direct photometric measurement instead of by illuminometer measurements.

An accurately constructed photometer placed upon this tube showed it to be operating at 12 hefners per foot, which is equivalent to 2388 total hefners and an efficiency of 1.4 watts per hefner power from the street mains. This figure is obtained by simply dividing the total watts delivered to the tube from the city service mains by the total number of hefners. This bunsen photometer consists of a black wooden box 5 in. square and exactly 3 ft. between light sources. The tube passes through one end of this box transversely while at the other end is located a certified standard Reichsanstalt hefner-von altneck amyl acetate lamp. If the losses of the terminal box are deducted, the actual efficiency of this tube, simply as a light source—which is the manner in which practically all other light sources are usually rated—reaches the remarkably high figure of 1.3 watts per hefner. When a Moore tube is diffusing its yellow light, one seems at least to be able to see far better than when it is producing the same hefner power of white light.

Fig. 10—Basement of department store

The useful illumination has been increased 220%, yet the current consumption reduced 22%; this amounts to a saving of 10c. per kilowatt-hour. At 65 hours per week this means $338.00 per year on this one tube. On the four tubes for the entire basement it means a saving of $1350.00 per year.

On account of the remarkable color qualities of the white Moore light, a request was made to change two of these yellow tubes over the china department to a white color, and the following comparative illumination tests were made between tube "C," 211 ft. long, when fed with pure carbon dioxide gas, and therefore giving a white light, and the ten 6-ampere, 60-cycle arc lamps provided with 12 in. spherical opalescent globes.

Fig. 10 is a photograph of this department taken solely by the light of the tube.

Illumination Measurements under "C," Tube Bamberger Basement

Station	Moore Tube	Arc Lamp System
1	0.91	0.34
2	1.71	1.73
3	0.89	0.36
4	0.75	0.40
5	1.06	0.63
6	2.18	1.51
7	1.31	0.97
8	0.47	0.45
9	0.49	0.29
10	1.11	0.51
11	1.96	0.54
12	0.88	0.57
13	0.66	0.23
14	0.63	0.32
15	1.71	1.11
16	1.25	0.43
Mean illumination (average hefner-feet of 16 stations)	1.12	0.65
Average variation from mean	37.5%	51.7%
" volts	227	122
Amperes	42	59
Watts total	5750	5000
Power-factor	61%	70%
Area square feet	4275	4275
Watts per square foot	1.34	1.17
Illuminating efficiency $\frac{\text{Mean hefner-foot x area}}{\text{watts}}$	0.83	0.55

Therefore the white tube is 1.5 times more efficient than the enclosed arcs.

The delicately colored china ware is now exhibited under exact daylight conditions, and the general illumination is a marked improvement over that furnished by the arc lamps. The fact should be emphasized that the arc lamps hung much lower than the tube and produced a bad effect. The arc proper of the arc lamps was 28% nearer the plane of measurement than the tube. With the tube there located it would also show an economy over the arc lamps of about 78%.

Although the above tests indicate that this system is now the most efficient light source known, nevertheless not only theory but experiments already made show that greater advances in efficiency are yet to be made. The best gaseous-conductors particularly adapted for selective radiation must be determined upon. For example, nitrogen has about twenty times the efficiency of hydrogen. A gaseous-conductor must also be selected that not only has proper color values but must maintain high efficiency over wide ranges of intensity; for example, mercury vapor (to say nothing of its color) is very inefficient in the long-tube system. It is only efficient at intensities which should be considered too high, and which is also the reason why the mercury tube is so sensitive to temperature changes.

Moore tubes are now used in lengths varying from 40 to 220 feet. The following curves show the watts per hefner for 40 feet to be 2.5, and for 220 feet to be 1.4, on the basis of a yellow light. Therefore when tubes are operating at 12 hefners per foot, which is the average intensity now used, tubes from:

40 to 70 feet use a 2-kw. transformer.
80 " 125 " " a 2.75-kw. "
130 " 180 " " a 3.5 " "
190 " 220 " " a 4.5 " "

In order to insure steady light, the power-factors of the circuits supplying these transformers average at present 65%. This is obtained either by using a shell-type transformer of special design with a leakage reactance of about 65%, depending on the size of the transformer required, or there can be used a standard type of core transformer, operated in series with a special type of adjustable inductance consisting of two opposing coils on the center leg of an iron core of the shell-type formation.

Feeder-valve solenoids of four sizes have been found sufficient, and are usually connected in series with the low-tension circuit of the transformer and inductance, although they are sometimes operated by the high-tension circuit.

Although the average power-factor is now about 65%, there is no theoretical reason why all these tubes should not operate at a considerably higher power-factor. In fact a very recent improvement in the valve which has entirely eliminated capillary attraction, has made it practical to adjust tubes to a power-factor as high as 84%—which is a decided improvement over some of the first tests published, and makes the tube far better than either the alternating-current motor or the arc lamp in these respects. Since all of the electrical factors of the entire system are based on the conductivity of the gas column, it is possible to vary the power-factor over a wide range simply by changing the degree of vacuum by regulating the amount of gas fed to the tube.

The following curves show the relations existing between the salient factors that have to do with the tube performances.

Curve *A* shows how the amperes of the low-tension side of the transformer at 220 volts vary with the length of the tube.

Curve *B* indicates that the actual voltage on the tube terminals for 40 feet is 3146, and for 220 feet 12,441 at 12 hefners per foot.

Curve *C*. Since the no-load transformer losses and also electrode losses become a larger percentage of the total watts as the tubes are shorter, therefore the watts per hefner grow less: that is, the longer the tube the better the efficiency.

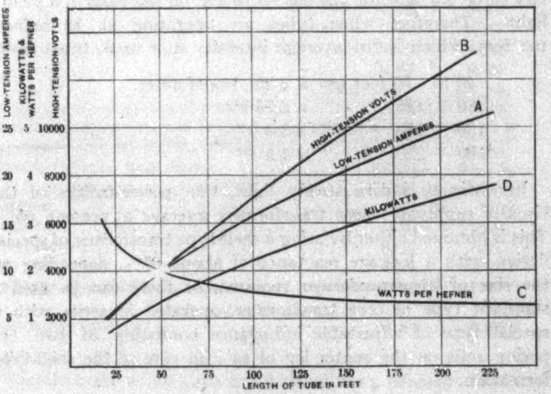


FIG. 11

Curve *D*. Doubling the length of a tube does not double the kilowatts required.

Curve *E*. These tubes soon become seasoned; that is, use up all foreign gases, and then their intensity remains perfectly constant for an indefinitely long period of time.

Curve *F*. The efficiency also remains constant.

Curve *G*. The efficiency does not vary over a wide range of supply voltage.

Curve *H*. The light intensity is directly proportional to the voltage, not as the square or the cube of the voltage as is the case with incandescent lamps. This is an advantage of great practical importance.

Curve *I*. The light intensity is nearly proportional to the watts.

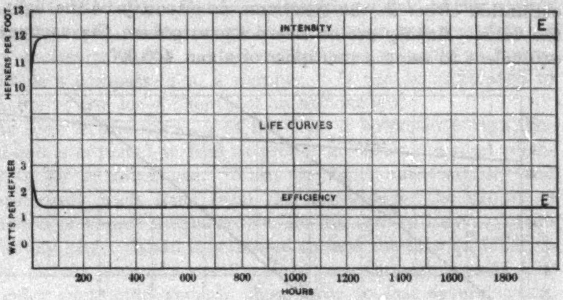


FIG. 12

Curve *J*. The light intensity is proportional to the tube amperes, and that a tube radiating 13 hefners per foot of yellow light requires three tenths of one ampere.

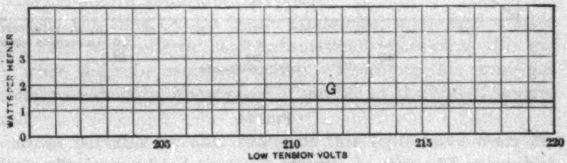


FIG. 13

The degree of vacuum required in these tubes is about 0.10 of a millimeter which, comparatively speaking, can be called a high vacuum. This vacuum is maintained within 0.01 of a millimeter or 0.00001% of an atmosphere either above or below the normal degree of vacuum. The solution of this very difficult problem of maintaining a degree of vacuum so nearly constant, was found by taking advantage of the fact that but slight changes in the vacuum cause enormous changes in the electrical resistance of the gaseous-conductor. For example, a tube 220 feet long at its lowest vacuum (0.11mm), takes 24 amperes, but at the end of every minute this has crept up to 25 amperes, when a new supply of gas causes the amperes slowly to drop again to 24. Of course it is impossible to detect this slight oscillation either in the steadiness or intensity of the light in the tube. Making use of electricity to govern the vacuum is equivalent to using a multiplier of about 400,000.

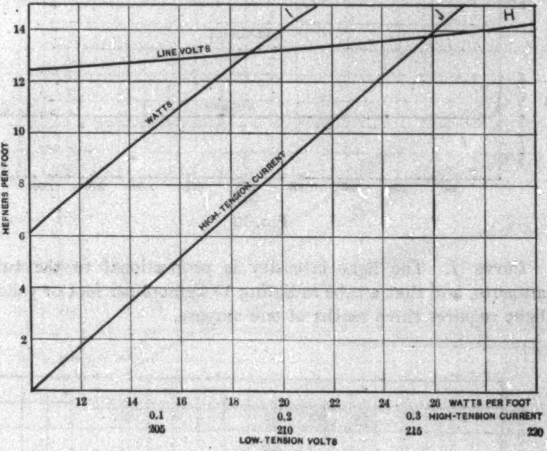


FIG. 14

These long tubes are built in place by hermetically sealing together 8 ft. 6 in. lengths of 1.75 in. glass tubing, with walls $\frac{1}{16}$ in. thick, by means of a new blast illuminating gas-fire or double-flamed torch. This work can be done rapidly and cheaply since in a 100-ft. tube about a dozen joints are needed and only about two minutes are required for each one. This has necessitated the development of a new trade: namely, "glass plumbing."

The two ends of the tube within the terminal box each contain a graphite cup electrode 8 in. long. Immediately in front of one of these electrodes a branched small-bore tube extends to the bottom of the feed valve, see Fig. 3, and the other branch is available to be connected temporarily by a rubber hose to a new small portable oil vacuum-pump. The electricity is turned into the tube shortly after the pump is started and the amount of light resulting indicates in a measure the degree of vacuum in the tube. But in investigating a field of this nature a simple, rapid, and accurate vacuum-gauge was found to be very necessary, and it has proved to be as valuable an instrument as a compass is to a mariner. It can be calibrated to measure to one ten-millionth of an atmosphere.

As soon as the vacuum of the tube is sufficiently high, the feed-coil is adjusted to feed at proper intervals the right quantity of air or other gas. When the light automatically and continuously feeds itself from the atmosphere, the supply of which is of course inexhaustible, its life can be said to be indefinitely long. When it is desired to feed the tube on nitrogen only, the air is simply made first to pass through a small iron cylinder containing enough phosphorus to last several years. Should a longer life than this without any attention be desired, several cylinders can be used in series and these can be renewed an indefinite number of times at a negligible cost. Effectually to prevent more than is necessary of the atmosphere from coming into contact with the phosphorus, or being continuously in contact with it when the tube is not in use, it has first to pass through a small mercury trap.

To feed the tube CO_2, a bottle containing a piece of marble and a little hydrochloric acid automatically generates this gas only when the tube requires feeding. Therefore this small gas generator needs only a new piece of marble at the end of several years.

Various portable or unit forms of this light have been designed. For example, the one shown in Fig. 15 resembles somewhat an arc lamp. It operates at 220 volts and requires 25% less watts yet gives 25% more useful illumination than an enclosed arc.

The automatic feeding-valve is of course applicable not only to alternating-current vacuum tubes but also to direct-current vacuum tubes. It can be made invaluable for all kinds of vacuum-tube apparatus, such as X-ray tubes, vacuum oscillographs, wireless telegraphy or telephony transmitters and receivers, vacuum or vapor rectifiers or lamps.

A careful analysis of this system of illumination in general, discloses the large number of advantageous features it possesses. It is the first artificial light that can rightly be called imitation daylight. Natural daylight is the only ideal light that can ever exist and the eye accords with it, therefore the nearer any light source approaches it the better, and vice versa. The absence of the red rays in daylight, for example, would far from improve it. This system is so much nearer natural light imitation that it is in a class by itself. But these tubes furnish a perfect diffusion of light because the light radiates from such extremely large areas as compared with all the old style spots of light, and therefore if desired a more nearly shadowless light can be produced than any other known means.

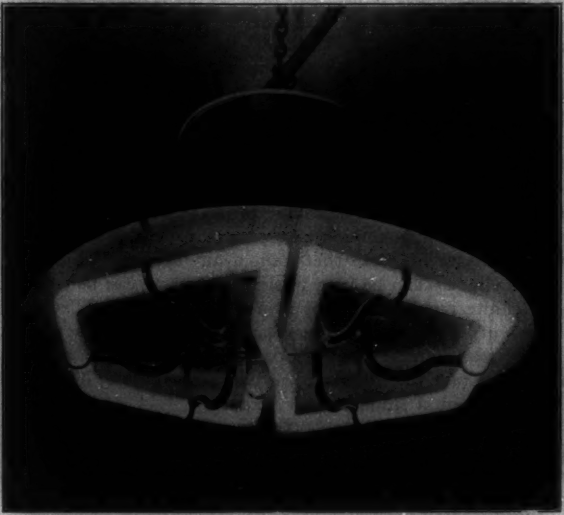


FIG. 15—A small unit of Moore light

The recently appearing types of incandescent lamps having improved efficiencies, such as the osmium, tantalum, zircon, graphitized carbon, tungsten, osmin, osram, titanium, and helion lamps are all obtained by causing solids to get overheated due to electricity passing through them. These new lamps—all based on an old principle—are only of transient interest, an interest of a vastly lower order than the interest that should attach to obtaining illumination by electricity passing through, not solids, but gases. They will not bring about a permanent radical change in the lighting situation. But such a change is now gradually being brought about by the vacuum-tube. However, by this it is not meant or claimed that all other forms of light will be abandoned. The candle business is larger to-day than ever before, and history shows that the electric lamp has interfered very little with gas. But changes must come. Each form of light has its own particular sphere of usefulness, which varies in size in accordance with its intrinsic worth and age. Some are just starting on their campaigns of usefulness, and others have reached their prime. Light resulting from gaseous conduction, it can truly be said, is right both theoretically and practically and therefore will probably survive for centuries.

It is simply claimed that this new system of electric lighting gives the up-to-date illuminating engineer one more available method for solving some of his problems and that some of its fields, as is the case with all other lights, are exclusively its own.

It should be remembered that the enclosed arc rapidly displaced the open arc, due to better diffusion and lower maintenance cost, notwithstanding a 50% loss in efficiency, but this new system in turn excels the enclosed arc in all of these factors.

The recent high efficiencies that have been obtained by other forms of illuminants have always been gained at the loss of some other salient factor; for example, such as life or color, but not so with this tube light. It is based throughout on thoroughly well known engineering principles that are properly applied. "The proof of the pudding is in the eating thereof," and the proof of every electric light is the illumination thereof. The term spherical candle power manifestly cannot apply any more logically to a long tube than can the law of inverse squares be properly applied to its light emanation. It is an indication of broadmindedness to have a complete indifference for all new forms of lights that have even a higher intrinsic brilliancy than the older forms with which we have long been familiar.

In this connection it is well to notice that many of these new forms of spot lights have enormous intrinsic brilliancies, because it is impossible to make them in lower candle powers. Besides the disadvantages of the high candle powers of these new point light sources, mechanical difficulties may make the ordinary used voltages impracticable. Few persons realize how comparatively little need there really is for small units of light, such as were contrived and used by our forefathers.

Abundant light is becoming more and more of a necessity and less of a luxury every day. There will always remain a small field for localized light sources, but so long as any new form of light is in the form of a spot; that is, so long as it is a highly concentrated light source, it is not worthy of much serious consideration so far as the great bulk of the lighting that is now needed by commerce is concerned. Large areas represent at least 80% of the lighting business. They should be illuminated by diffused light, therefore the only proper procedure is directly to generate a diffused form of light; that is, use a large and cool vacuum-tube, not a very small and a very hot filament and then try to scatter or soften its light and thereby waste about 50% of it, either by a diffusing globe or a reflector of some kind, to avoid glare. The long-tube system has the necessary natural characteristics that make such devices superfluous. Its enormously greater area is responsible for its correspondingly low intrinsic brilliancy.

Since it is possible and practicable to use these tubes graduated from an intensity of light per foot that is almost negligible up to 30 or more hefners per foot, it is impossible to state arbitrarily just what is the intrinsic brilliancy of a Moore tube. The average long tube now in use operates at 12 hefners per foot. The following table compares the tube with some other illuminants on the basis of hefners per square inch.

Moore light	at 6 hefners per foot	0.33
	at 12 hefners per foot	0.66
	at 36 hefners per foot	2.
Cooper Hewitt mercury tube		19.
Incandescent filaments		250.
Nernst glower		600.
Arc crater		10,000.

Some authorities have stated that an intensity greater tha about 5 hefners per square inch is beyond the theoretically correct limits, therefore this light is the only one that has a low enough brilliancy not to fatigue the eye. This has also been demonstrated by practice. It is remarkable that an intrinsic brilliancy as low as 0.33 per square inch is commercially thoroughly practical. Fig. 16 shows a tube that has been operating at this low intensity for over two years. It was also the first tube to be operated on alternating current from street mains. Even at this low intensity, the store is far more brilliantly and satisfactorily lighted than with the 16 c-p. incandescent lamps hanging low on flexible cords which were formerly used. So far as primary brilliancy is concerned, the tube far excels all other electric lights—all of which certainly need to be amply equipped with diffusing shades, etc.

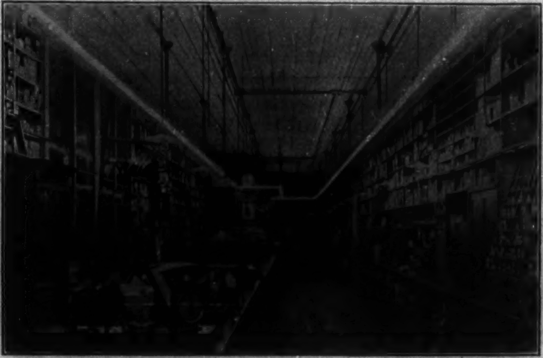


FIG. 16—Interior of hardware store

That great progress has been made in tube lighting is clearly proved by calling attention to the fact that the tubes in the "Moore Chapel" at the Madison Square Garden Electrical Show of 1898 operated at only ¼ of a hefner per foot while now a hundred times this intensity is easily reached.

Posterity will probably comment on the boast of one of our greatest illuminating companies, that it had to screen every light source in its model new building. Vacuum-tube illumination will obviate the necessity of a law prohibiting all kinds of glaring lights.

Illuminating engineers should not lose too much time by giving undue attention simply to the utilization of light, but should also rapidly come to a realization of the prime importance of the best methods of producing artificial light.

The Moore light is generated in such a manner that it needs no unsightly and expensive auxiliary apparatus either to distribute it by reflection, or to diffuse and soften it. It should be borne in mind that illumination from gaseous-conductors is a comparative infant in the commercial world. There is a marked difference between the illumination produced by a Moore tube and intense-point sources. This very marked contrast is shown best by suddenly throwing off the tube light and immediately throwing on incandescent lamps—especially if there are many of them and bare, and suspended by flexible cords.

After becoming accustomed to the tube light, workmen, whether machinists or employees in packing and shipping departments; very much appreciate the fact that they "can't get into their own shadows." For reading addresses or markings on loading or shipping platforms it can scarcely be surpassed.

This tube lighting accurately resembles cove or concealed lighting, yet there is no necessity for concealing the tube; should it be desired to conceal the source of light the cove itself is not needed, because all that is necessary is to place an opaque reflector on the lower side of the tube so that all of its light would be thrown toward the ceiling and illuminate the room therefore entirely by reflected light.

Incandescent lamps were originally placed behind coves because of their objectionable high intrinsic brilliancy, and the tendency is to allow the sins of the incandescent lamp to be visited upon the tube. The only reasonable excuse for placing a tube behind a cove is that the light source is concealed; but even this reason is not logical, because the intensity of the tube can be adjusted to be but little brighter than the ceiling is as a reflecting surface. Take for example the tube now lighting this hall. It is in front of the cove or cornice, not concealed in any way, yet its simplicity prevents it from being obtrusive. It harmonizes with its architectural surroundings and its height places it entirely out of the direct line of vision. Even though it be deliberately stared at, it does not dazzle the eye in the least nor distract one's attention as does the dim and streaked ceiling when the incandescent lamps are used. The most common kind of natural light is almost shadowless and always pleasing, as is also the lighting of many large areas by means of skylights, and so are artificial imitations of diffused daylight if made intense enough. A lack of uniformity in intensity does not rest the eye.

All authorities insist upon the avoidance of bright spots. This is accomplished by other systems at an enormous sacrifice in efficiency. Take for example the really beautiful lighting of many auditoriums using light diffused through glass ceilings. However, from the four standpoints of efficiency, simplicity, safety, and first cost, a little thought would convince the most skeptical of the enormous advantages, both in theoretical conception and practical application, of simple exposed glass tubes which would accomplish the result sought after equally well, yet at an enormous saving in operating expense.

It is the blinding brilliancy of the mercury tube that makes even a direct glance at it so very harmful to the eye. It is true the mercury tube is a light-source of larger area than all point sources, but a careful analysis will clearly show that in this respect it is but a short step in the right direction, and that its area for a given quantity of illumination will have to be multiplied a score or more times, as it is in the Moore light, in order to obtain an intrinsic brilliancy low enough to meet conditions both theoretically and practically correct.

A study of the history of the development of all light sources shows the vacuum-tube to be a logical conclusion of the progress of evolution. All portions of a long Moore tube are uniformly luminous. It has a governable intensity from zero to dazzling brightness; therefore any theoretical specifications can be met in practice by resorting, for improved methods of illumination, to the gaseous-conductor, not to a solid one. Carefully tracing the evolution of all forms of light from remote ages down to the present time as regards the following seven most important factors: diffusiveness, color, steadiness, absence of heat, efficiency, safety and first cost, all—clearly prove this long tube system to be a natural sequence and that the times are now ripe for it.

Widely spaced 50- and 100-c.p. lamps were commonly used twenty years ago, but custom and necessity gradually changed them to 8- and 4-c.p. lamps. Next they were placed close together in rows and then laid horizontally (as they are behind the coves of this room) clearly pointing to their natural successor in the direct line of progress; namely, the tube.

The arc lamp has changed from, first, the unsteady short open arc, to the much longer enclosed arc which multiplied the area of the light source many hundred times, to the enormous "diffusers" now used to improve as much as possible what I believe to be the fundamentally wrong principles of arc lamps and incandescent lamp clusters. The flaming arcs go one step further both in lengthening the arc proper and increasing the apparent light source to the entire area of a large globe. The Moore tube virtually consists of an "arc" drawn out to a length of several hundred feet.

Steadiness is a factor of vital importance to any form of light, and in this respect the long tube is excelled by none. Of course it does not flicker like an arc lamp and is much less affected by voltage variations than all forms of heated solid conductor lamps.

Stroboscopic tests of the light of the tube reveal an image better than that obtained from enclosed arc lamps, notwithstanding the fact that the heat-constant of the tube as the current wave passes through zero is less than that of any other form of light. Therefore when the supply switch is opened the tube light "goes out" quicker than all other lights, a fact which should be valuable for signalling but which also in a measure explains the high efficiency of the tube. Tubes of this nature will operate successfully on all frequencies, but at frequencies as low as 25 cycles the images will probably become too pronounced unless two- or three-phase currents are available, in which case by the use of multiple tubes the images of moving objects are entirely removed. The highest frequency in use at present for operating these tubes is 480 cycles, and is furnished by a motor-generator on 220 volts direct current. Careful tests on various frequencies up to about 10,000 cycles have shown that the number of alternations of the current used to excite these long tubes has nothing to do with their efficiency.

The only commercial and proper method of comparing all sources of light is on the basis of their ability to produce useful illumination, and not by any other basis. I have advocated for some years past the comparing of all lights by measurements of illumination and not by candle powers, and now see indications of this procedure becoming standard. The term hefner-foot will soon replace the unsatisfactory candle power, and contracts for lighting any area will be based on specifications calling for a definite intensity in hefner-feet on each square foot or square yard of the area to be lighted. This is far more practical than agreeing to furnish a lamp which is supposed to require no more than a certain number of watts per candle power, at the beginning of its life. All light users want to deal with terms that have to do with useful light, and this is one reason why the term " watts per candle power " has always been so extremely unsatisfactory. There should be used a single commercial quantity or figure that would correctly express the " illuminating efficiency " of each and any system of lighting used to illuminate a given area. If the area, and, therefore, all of its accompanying reflecting surfaces be changed, the relative values of this figure for each system is also liable to change, because some systems (for example arc lamps) are more benefitted, comparatively speaking, than are others by certain reflecting surfaces and other local conditions. Such a figure or value is readily obtained by dividing the average of the hefner feet measured at a suitable number of stations by the watts per square foot. This method will finally be widely adopted not only by illuminating engineers but also by the intelligent public—now that simple and perfectly self-contained illuminometers are available. The term hefner-foot is preferred because the hefner is the only practical primary standard. There is no longer any excuse for using the term candle power, and it should rapidly be dropped. The foot is still the commercial unit of length in this country.

If incandescent lamps were generally used as individual light sources, then watts per candle power would be the salient term, but since the vast majority of incandescent lamps are not used individually but simply as inconspicuous parts of a system of illumination, then the average hefner-foot becomes the factor of prime importance: that is, the illuminating efficiency, not the efficiency of an illuminant. We should be a little concerned about the specific efficiency of the lamps behind the cove in this hall, but very much interested in the ability (that is the efficiency, of the incandescent system as a whole to produce the result sought after: that is, to illuminate uniformly and without glare every square foot of this floor with a minimum expenditure of energy. Watts per hefner-foot is the important factor, not watts per hefner.

I believe that the proper way to compare all forms of illuminants would be approximately on the following basis:

1. The area to be lighted should be about 40 by 80 feet, and of approximately the shape indicated by these dimensions.
2. The illuminants must not extend below a horizontal plane 10 ft. above the floor.

3. The award is to be made entirely upon the results of illuminometer tests in a plane 30 in. above the floor and the stations of which are to be located as follows: ten equal spaces on the center line of the longer dimension, ten equal spaces on the center line of the shorter dimension, and ten equal spaces on the diagonal. The average of these thirty readings is to be divided by the total number of kilowatts used from the street mains by each form of illuminant, and the highest quotient (light units per energy unit) will determine the placing of the award.

It is not surprising that the tube should surpass the incandescent lamp both in efficiency and diffusion in the lighting of an area of this size, because the incandescent lamp is wrong theoretically—too far away from natural light—it is too small, too red, too hot. The highest temperature at which glower lamps operate would make them do better, about half as well as the tubes. So with all the incandescent types of lamps, to say nothing of the bother and expense of replacing them, either in whole or in part. Arc lamps would be out of the race, because of inefficiency, glare, flickering, wide variations in candle power between feedings, poorly distributed light, noise, dirt, etc., besides the maintenance expense of recarboning and cleaning. Compare the simplicity of the method of obtaining diffused light by means of the tube with the really commendable attempt to obtain a comparable diffusion by equipping arc lamps with concentric diffusers that are as enormous as they are crude so far as the means to the end is concerned. Especially is this the case where light balancing selector diffuser ceilings are installed. They very pointedly indicate the need of a tube light.

During the first year of its use—1903—the gaseous-conductor of the Moore tube was produced by chemical means, which has been comparatively recently superseded by the automagnetic valve. Therefore the lapse of time since the first automatically fed tubes were installed being so short, it is not now possible to state definitely what their final life will be, beyond the general statement that some of these tubes have already been in operation over 4000 hours without change, and that there are good reasons for believing that they should continue to run at least again as long, which is a much longer life than any other form of illuminant yet invented. This whole system is one with an exceptionally large number of variables, and this also applies to its life, because it depends partly on the intensity at which the tube is operated and the particular gas used. Since air or other gas is regularly admitted to the tube and changed to some solid form, due to certain electrochemical reactions, it is certain that the time of operation without any attention whatever cannot be prolonged indefinitely. Before adopting the chemical method of obtaining a nitrogen supply for the long tubes, it was stored under about three pounds pressure in a small tin cylinder placed in the terminal box, which supplied an average tube before needing to be recharged for considerably over a year. Therefore the quantity of gas (nitrogen for example) necessary to support a light of 12 hefners per foot is so small that a tube of average length should remain in perfect condition for a number of years before it would be expedient to remove the small quantity of dark-colored powder which may have accumulated only within or near the graphite electrodes.

When a tube has been properly exhausted, the discoloration in front of the electrodes should not at any time extend more than two or three inches. When a tube is striated, it indicates that other gases are present that are foreign to the one decided upon to be used.

The light source of all other lights needs to be renewed, but in this case the light-giving tube itself will last an indefinitely long time, since it is neither consumed nor becomes blackened in the least. Should any renewal be required it is at the electrode which can be replaced comparatively cheaply.

The cost of a long-tube installation, due to its being construction work, varies with its location, its length, its shape, the intensity of the light required, the kind and number of fixtures desired, and other local conditions; but is already less than the cost of a first-class incandescent lighting system with its necessary wiring, fixtures, and shades. Eventually it will be far cheaper. It should be borne in mind that the first cost of this tube corresponds with the entire cost of an incandescent lighting system—its iron piping, wires, cut-outs, fixtures, shades, and lamps—and also that the first cost should be considered only in connection with the fact that in many instances this tube will pay for itself several times over during its first year of use from the amount saved on what the current bills would have been if incandescent lamps had been used to produce the same amount of useful light.

This system is extremely simple. Only two parts are essential: the light-giving tube and the terminal box. We are so thoroughly familiar with the ordinary incandescent lighting system that it is hard for us to realize that it has become really very complicated with its hundreds of different devices. Its most enthusiastic supporters a few years ago would have declared the present conduit system as entirely prohibitive, especially when concealed. But now almost all of it can be eliminated by simply installing a light-giving tube, even after the decorations have been completed, as was done in the last few days in this room.

Architects have long considered electric wiring problems one of their most vexatious burdens. Now a terminal-box can be used as a center of distribution from which there radiates a number of long tubes to illuminate portions of the same floor, or extend to floors above or below. A tube provided with a reflecting enamel on one side is a far simpler device for lighting show windows than the extremely cumbersome combinations of rows of incandescent lamps with mirrored reflectors in sheet metal troughs, etc. This tube system has no complicated mechanism like arc lamps, for example, but instead the only moving part is the displacer of the feeder valve which in its design is about as near being frictionless as is conceivable. Normally, its movement is less than 1/32 of an inch, and some of these valves have required no attention and yet have been in active use over 4000 hours. They should continue to operate an indefinitely long time.

As a scientific instrument this automatic valve is another combination of ruggedness with marvelous sensitiveness, in which respects it resembles a telephone receiver. The very nature of this system is such that the liability of a normal tube being broken is very slight; yet in case of accident a new piece of tubing can be quickly and cheaply inserted. The ideal and rapidly approaching final position of such a tube is against or almost against the ceiling, the illumination then most closely resembles light coming from the sky. But many users, notwithstanding the high efficiency of the tube light, desire to reduce their bills still further by using a less number of hefners per foot, and support the tube on long fixtures. When a tube is cracked or broken the inrush of air of course instantly extinguishes the light, but the electrical apparatus is in no way disturbed.

This is a hardy piece of apparatus, not a delicate mechanism like the incandescent lamp. Glass tubing properly supported is far stronger and more flexible than most people realize. The voltage on a tube's terminals can either be raised or lowered without harming in the least either its life or its efficiency. The conductivity and light of these tubes are practically unaffected by temperature changes, especially those emitting yellow light. Another installation which depicts a quality of this light peculiarly and exclusively its own is fifty feet of tubing skirting the bottom of a large aquarium. The fishes are not disturbed in any way by its presence; that is, neither by shocks nor by heat. Scientific glass experts predicted great trouble from expansion and contraction but neither the direct summer sun or long icicles has had any apparent effect. This is the only form of light from which icicles can hang, which indicates its approach to light without heat. Neither moisture nor fumes affects these tubes. There is no multiplicity of sockets and wires to become damaged or short circuited, and the tube can be most easily cleaned.

The light-giving tube itself is harmless either to life or property. The terminal box is made of steel with a slate bottom so that even though the small transformer within it should completely break down, smoke only would result. It is impossible for the exterior of the terminal box to get hot enough to set fire to anything. It is carefully designed so far as ventilation is concerned, and is always mounted so that there is an air-space all around it. With this loop tube system, aside form the ordinary short feed circuit, there is no part of it to be classified as a "risk" since all of the purely electrical apparatus is securely contained in a fire-proof terminal-box.

Fig. 17 shows the terminal-box, but it also shows, inadvertently, though most strikingly, the contrast between the simplicity of the tube and the complexity of the network of wiring on the ceiling which it has supplanted.

Owing to the high efficiency of the tube and the large area from which any heat accompanying the light can radiate, the temperature of the tube is remarkably low, being in the neighborhood of 100° fahr., therefore it cannot injure either perishable goods or the health of those working under it. In basements for instance in summer time, the fact that only about one sixth as much heat is dissipated as would be if incandescent lamps were used is a matter of prime importance to the problems of ventilation, etc. Large areas like department stores for example, can now be electrically lighted without an inch of wire within their walls, by placing the technical boxes of these tubes on the exterior of the building. It is wireless lighting. It was of much scientific interest to note that tubes at the same degree of vacuum with the same amperage flowing produced a widely varying quantity of light as the kind of gaseous-conductor was varied and that the temperature of the tube was higher with the gases producing the most light.

This system, from a number of standpoints possesses great flexibility. This is illustrated, so far as the distribution of the tube is concerned, by Fig. 18, which shows the layout of tubes on the mezzanine floor of a public building office. These remarkably varied shapes and lengths are due to the necessity of light being located to suit each particular desk, table, set of files, etc. Since tubes can be made of any diameter and form, the artistic possibilities of electric lighting are multiplied many fold.

FIG. 17—Exterior of terminal-box.

Flexibility is again demonstrated by the facts that the intensity and also the color of these tubes can be varied over wide ranges. The higher refinement of the art of illumination is bringing into view more and more prominently the color of all light sources. Not their individual colors, however, but the color values they give to surrounding objects, is fast becoming, next to efficiency, the most important fact in connection with any light. This light is the first and only illuminant the color of which can be changed at will over a wide range. This is accomplished by changing the character of the gas within the tube. If a tube is permitted to feed itself on plain air, an efficient pink light results, but if the air is first caused to pass through a cylinder of phosphorus to absorb its oxygen a golden-yellow light is produced that is the most efficient light source known. When operated at higher intensities than 12 hefners per foot,

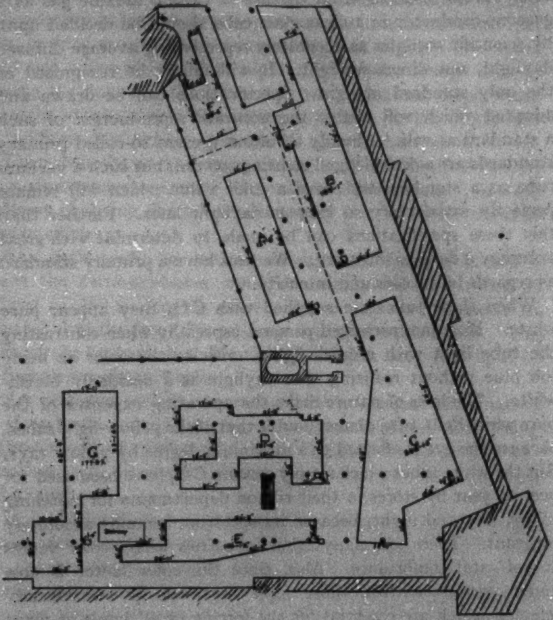


FIG. 18—An installation showing various shapes of Moore tubes.

and viewed in line with incandescent lamps, it is apparent that the colors are about the same as well as the color values of all objects viewed under it.

Although our firm purpose should always be to imitate daylight, nevertheless its color values are not constant quantities at different hours of the day. Fortunately, the spectrum and color values resulting from the use of carbon dioxide gas as a gaseous-conductor in a clear glass tube should be decided upon by scientific societies as accurately representing average diffused daylight, not direct sunlight. It will finally be recognized as the only standard of light. Specifications can be drawn and adopted which will enable the accurate reproduction of such a standard at will. Already all of our present so-called primary standards are acknowledged as being too red, but such a vacuum tube as a standard will have a color value which will remain perfectly satisfactory so long as daylight lasts. Further than this these specifications can be made to determine with great accuracy a definite intensity. We thus have a primary standard as regards both color and intensity.

When these tubes are supplied with CO_2 they appear pure white. Most inexperienced persons, especially when contrasting the tube light with reddish lights, criticize the color as being too blue without realizing that daylight is a decidedly bluish-white. The laws of nature make the operating expenses of the pure white light tube almost double that of the yellow-light tubes, because the eye is effected to a maximum degree by yellow rays, But the white tubes which simply contain CO_2 have been used for over a year by stores in their ribbon departments for matching colors, day and night, because its spectrum remains absolutely constant. There are many other industries where color values are of vital importance. Also, since the color factor is now under perfect control, those light rays can be scientifically selected which are essential for the forcing of all kinds of plant life, flowers, fruits, and vegetables. The color of the light can be varied by feeding the tube any gas as each has its own spectrum, or by using multiple valves, etc., mix various gases within the lighting tube itself. White tubes are daily being put to most vigorous tests at the works of one of the largest silk dyeing establishments in this country, but no difference can be detected in the most delicate shades when matched either under the tube or in average natural daylight. For some time past artists have been mixing their colors at night under the white tubes. Portrait photographs are also being made under it that equal those of natural light. Since the yellow tube light is about the same as that of the incandescent lamp it is being used successfully by clothing merchants and florists. Also on account of its uniformity of intensity it has proved its superiority for photographic printing.

It is interesting to note how different the same tubes lighting an ordinary store window appear in the afternoon when the sun is shining and after seven o'clock at night. The tubes that are yellowish white at night time appear orange colored during the day, and the tubes that are a pure and dense white at night appear a pale blue during that day—in fact if exposed to brilliant daylight no light can be seen in them at all.

Users can obtain the exact quantity of illumination desired on a given area more easily than with any other system, because without changing the tube its intensity can be varied without loss in efficiency.

This light could be used in subways and tunnels, in which cases the terminal-boxes would be eliminated and miles of tubing in 100-ft. lengths placed end to end and operated in parallel directly from the adjacent high-potential mains. The eyes of the motorman would then be subject only to a light of definite intensity and color.

Art galleries, surgical operating tables, exterior illumination of ferryboats, street lighting, shop show-windows, advertising signs—all these and many other industrial and artistic enterprises will be vastly benefited by the application of this tube light.

It is believed and hoped that the ideas advanced in this paper are simply in the direction of progress. Aside from all theory, the facts show that electric illumination resulting from incandescent gases or vapors has vastly less limitations because their molecules or atoms are free to vibrate while those of solids are not, and therefore at the high temperatures necessary are subject to rupture. "The signs of the times" clearly indicate that we have reached the beginning of the end of lighting by solid conductors and the end of the beginning of lighting by gaseous-conductors.

DISCUSSION ON "LIGHT FROM GASEOUS CONDUCTORS WITHIN GLASS TUBES—THE MOORE LIGHT," AT NEW YORK APRIL 26, 1907

Gano Dunn: While we are waiting for the remainder of the tests which are to be made upon the tube and the lamps strung around the room, we may as well proceed with the discussion. I feel that we have been listening to the exposition of a new art. My mind goes back to 1893, 1896, and also to 1898, the time of the "Moore Chapel," when the Institute heard from Mr. Moore before. In those days what he had to show compares with what he shows us this evening as Stevenson's original "Rocket" compares with the modern Atlantic type of locomotive. Two years ago on entering the Madison Square Garden, I was greatly impressed with the appearance of a Moore tube in the lobby, and admitted then that I made a mistake in considering the Moore system not a success. I had had the impression that it was good only for illuminated signs and relatively unimportant work. The Madison Square Garden tube was a revelation.

We should be careful not to estimate the value of the Moore system solely by its efficiency. There are radical differences in the character of its distribution, its color, and its method of operation, from any one of which important advantages may spring. For instance, on account of its longitudinal source, the intensity of the Moore light does not vary inversely with the square of the distance, and from this follows freedom from shadows and a certain similarity to daylight.

The effectiveness of a luminous source should not be measured by how much light it emits, but rather by how much light it delivers where the light is wanted. A lamp of high intrinsic brilliancy, that is, of concentrated source, over-illuminates surfaces near it, while it under-illuminates surfaces somewhat removed from it. To the under-illuminated surface full credit is not given for such illumination as exists, because the eye usually rests upon this surface after having rested upon a brighter surface or possibly upon the lamp itself. There has to be an excess of light on surfaces near the lamp in order to bring surfaces away from the lamp up to the desired minimum of illumination. The excess illumination being unnecessary, is wasted. Worse than this, having fatigued the eye, it renders less evident the illumination that does actually exist upon the under-illuminated surface. The largely distributed source (a tube many feet in length) is what I had in mind when referring to lighting by Moore tubes as a new art. Other sources of light are not larger in volume than a nutshell.

We must be ready to see disadvantages in Moore's system as well as advantages, and I hope both will be clearly brought out in the discussion.

C. P. Steinmetz: The second part of this paper is extremely interesting, and I believe is a valuable addition to the literature of producing light by what may be called an improved Geissler tube. It is the old Geissler tube in the form of a commercial illuminant. If we look back on the history of Mr. Moore's work, we find that originally he produced a varying-in-pressure-contact, some kind of a flimsy device in a vacuum, and then proceeded to operate Geissler tubes at extremely high frequency, using motor-generator sets. Here at last we find the light at commercial frequencies, and in a commercial installation, taking its place as one of the commercial illuminants.

The paper gives the first actual engineering data of this kind of light, the energy, volts, and amperes and some data on efficiency, etc. The author gives comparative data on the illumination produced by the Moore tube and the incandescent lamp. Later on, comparisons are made between the arc lamp and other systems. I am not impressed with the comparative values given, except that they show that incandescent lamps and arc lamps can be installed in such a manner as to get very little light from very much power. That fact was known long ago, without having special tests made. If the installation of the incandescent lamp is left to the artistic sense of an architect, or to mere accident, such a condition will obtain, but the comparison is not fair. If an unsatisfactory incandescent light system, unsatisfactory by reason of poor installation, poor type of reflector, etc., is replaced by an intelligently installed system, the advantages of the latter will be apparent. I have no doubt that if Mr. Moore's hopes are fulfilled, and in future all the plumbing establishments in cities and villages and country towns have a department of glass plumbing, and if a future illuminating engineer goes around in the country towns or villages, he can use the old 3.1 watt incandescent lamp and replace very many Moore tubes installed by the local plumber and show a vast improvement in efficiency by intelligently installing with proper reflectors, the old incandescent lamp. That does not mean anything: it only means that if the old installation of incandescent lamps was made by an illuminating engineer, he should have his license withdrawn, if such a thing existed.

Some illuminating efficiency measurements are expressed in terms of in hefner-feet. I regret the use of the word hefner here. In the United States illumination is measured in British candles, not in hefner candles. The hefner candle is 0.88 times the British candle, so that the values given in the paper have to be multiplied by 0.88 to bring them to the American standard of illumination. Mr. Moore finds an illuminating efficiency, mean hefner-foot per watt, of 2.15. One British candle as a source of light of one mean spherical candle-power gives an illumination of one candle-foot at one foot distance. One mean spherical candle-power then gives 4π candle-feet, or

12.56 candle-feet, dividing this by 0.88 to reduce it to hefner-feet, gives 14.28 hefner-feet per mean spherical candle-power. Mr. Moore gets 2.15 mean hefner-feet per watt; reduced to mean spherical candle-power, this means that his light consumes in the useful illumination 6.64 watts per mean spherical candle-power, if one counts only the light which reaches the illuminated plane. It means, then, that a very considerable part of the light is thrown away, absorbed by the walls, ceilings, etc. I do not believe it is an unfair estimate, for such a class of light, to say that 50% of the light is wasted. That is estimating that half the flux or light radiated by the tube reaches the plane of test. That would give an efficiency of 3.72 watts per candle.

It is instructive to apply this to the last column headed "Incandescent system," and that will bear out what I stated, as to what should be done to the illuminating engineer who installed these incandescent lamps, which show but 0.39 hefner-feet per watt.

Assuming 4 watts per mean spherical candle-power, which is a reasonable value, one should get, for all the useful light in the illuminated plane, 3.57 hefner-feet per watt, or eight times as much as is given here. It follows that if these were four-watt incandescent lamps they would lose seven-eights of the light before the light reached the illuminated plane. This explains the enormous difference in illumination by these two sources.

The values given in comparing the Moore tube with the arc lamp system, allowing for the Moore light half of the light wasted before it reaches the illuminated plane, indicate an efficiency of 2.56 watts per mean spherical candle-power, and 14.8 watts per mean spherical candle-power of the flux of light sent by the arc lamps on to the illuminated plane, a ridiculous value. It seems probable that the arc lamps were hung without reflectors or diffusers anywhere on the ceiling.

In the photometric tests the most efficient tube gives 1.4 watts per hefner-foot. That means at right angles to the tube. The light in the equator of a linear source is $\frac{2}{\pi}$ the average or mean spherical. Dividing by 0.88, to reduce to our standard of light, the British candle, gives 2.5 watts per mean spherical candle-power or per lumen, that is, per unit flux of light. The test of the illumination measurements gave 2.56, and probably this is about the efficiency of light production of the Moore tube.

Leaving out all illuminating questions, and merely considering the matter of the flux of light per watt, the next point to consider, then, would be the distribution of the light. But the first and important question always is how much light is got from the source of light? The best efficiency of the Moore tube seems to be about 2.5 watts per unit flux of light, that is, per lumen. This gives about the same efficiency of the tantalum lamp, or not very far from the enclosed arc; it is better than the carbon filament incandescent lamp, but inferior to the tungsten lamp.

The carbon dioxide tube is recognized as less efficient, and I do not need to refer to it. I desire here, however, to draw attention to the fact that the efficiency of the Moore tube has arrived at that stage where it is now in the range of commercially practical efficiencies as an illuminant. It is not any more an inefficient illuminant, although it naturally is not of the same class in efficiency as the mercury-arc lamp.

Efficiency of light production is, however, not the only thing to consider. The essential question is to make use of the light, and that leads to the question of distribution. A useful feature is the low intrinsic brilliancy which eliminates the dazzling and blinding glare, with this new source of light, while the tungsten filament, for instance, is rather bad in this respect. However, too much importance must not be attributed to this feature, because even a point source of light can be diffused by diffraction or diffusion, a holophane or frosted globe. Light is lost by this procedure, but if five hefners per square inch is considered as a proper low intrinsic brilliancy, a 32-c-p. tungsten lamp enclosed in a frosted globe three to four inches in diameter brings the intrinsic brilliancy of the whole globe down to five hefners per square inch, probably less, with from 15 to 20 % loss of efficiency, and still leaves an efficiency far higher than that of the Moore light. You can allow in favor of the low intrinsic brilliancy from 15 to 20% lesser efficiency, but not more, because you can get low intrinsic brilliancy by diffraction with this loss.

The last part of the paper is a rather voluminous discussion of illuminating engineering matters, which would be very essentially improved by greatly shortening it, and would then have more value by making it more probable that the busy engineer would read through it, and there are some features in it which are well worth reading, but they are buried among so many pages that life, as a rule, is too short to afford time to go through it. I read it, however.

The author refers to the blinding brilliancy of the mercury tube. I have never noticed that. I am using the mercury tube exclusively as an artificial illuminant for any work that I may have to do. I would not think of using any other source of artificial light and find it by far the best. Further, the author says:

> The only commercial and proper method of comparing all sources of light is on the basis of their ability to produce useful illumination, and not by any other basis.

I should challenge that. This is the ultimate purpose, and the customer who makes a contract to light his premises with an economical amount of power specifies this; but to the illuminating engineer who takes the contract to put in the lights, the important question is what type of light to employ, so as to use the least amount of power to produce the best illumination. For the illuminating engineer the most important question is what source of light gives the maximum flux of light for a given amount of energy, the maximum quantity of light per watt. The next question is, whether this source of light is suitable for direct distribution, or how much of the light may have to be wasted so as to get the proper distribution. The statement quoted above rather begs the whole question of illuminating engineering.

The statement is made that photometric tests do not amount to anything. That is an old statement, and has been repeated very often, but I do not think that anyone will accept the dictum that the mean spherical candle-power does not mean anything. While with a light source of this kind one cannot speak of mean spherical candle-power, one can speak of the total flux of light; and it does mean something to determine how much total flux of light can be got per watt; indeed, as stated above, it is the most important question in the matter of artificial illumination.

So we must know how many lumens per watt we get, and since the lumen is the total flux of light which one candle-power gives, it is a convenient substitute to speak of mean spherical candle-power; but when we speak of mean spherical candle-power with a linear source of light, as the mercury lamp or the Moore tube, the mean spherical candle-power means the unit of flux of light, or the lumen, and that is independent of the shape of the source of light.

In regard to the proposed method of comparing lights, by lighting a room 40 by 80 feet, for instance, in lighting my house this would not help me much, because my house has no room quite so large. Light is used not only to illuminate stores and halls but a great deal is used for other purposes. However, if illuminants are to be tested in a 40-by 80-ft, room, to find out which illuminant requires the least energy to give a certain illumination in such area, there would be found, first, the mercury lamp, then a long interval; then the tungsten lamp, and another long interval; and then the Moore light, the tantalum lamp, and the enclosed arc, and finally the different other metal-filament incandescent lamps and carbon lamps and Nernst lamps, etc. So after all, neither the Moore light, nor any incandescent light, has the same degree of efficiency as the mercury lamp.

While criticising the character of the paper, especially the first and third parts, one must not forget that the second part contains some very valuable and important information. Mr. Moore is to be congratulated on the great advances he has made in the last few years, in reaching commercial conditions with his light, commercial frequencies, commercial voltages. There are some things which have not been especially dwelled on, among them the remarkably ingenious valve arrangement of feeding air or gases into the tube and maintaining a constant vacuum. We must remember that the vacuum in this tube is about $\frac{1}{8000}$ of atmospheric pressure. To maintain constant such a low pressure, not visible any more in a mercury gauge, and maintain that constant within a few per cent. is a very remarkable achievement. So while criticising a part of the paper, I do not want to convey the impression that I do not admire the work which has been done by Mr. Moore. I recognize that he has made enormous steps in advance since we last heard from him. I also very much appreciate the very ingenious way of feeding these gases into the tubes, and the method of getting rid of the oxygen in the air, and feeding nitrogen or carbon dioxide. These are remarkable and ingenious devices which can only be admired.

Percy H. Thomas: Mr. Moore, has, I believe, given us a very timely and generally satisfactory paper. In addition to the general information about and description of his actual apparatus, he has called attention to a number of valuable points. For example, a great many people do not realize the value of lighting a room from one outlet and doing away with the pendants and fixtures and small outlets. Not only is a great deal of expense saved, but a good deal of fire-risk as well. The elimination of the cost of multiple outlets and many units, fuses, cords, etc. is one of his largest factors of economy over incandescent lamps. This is an advantage that his system of lighting shares in some degree with the Cooper-Hewitt light.

Mr. Moore has always maintained, and very emphatically, that his tube produces artificial daylight, and he apparently expects us to assume that there is no difference between the Moore light and daylight. This statement should be challenged. In the first place daylight gives practically a continuous spectrum. Mr. Moore's light comes from gases and must be a banded spectrum, a few colors well distributed over the spectrum, it is true, but still unable to give the same effect as a true continuous spectrum. How much practical importance this deficiency will be found to have can only be determined when a sufficient number of commercial installations have had considerably extended use.

In the second place, the tube does not give a strictly perfect diffusion, though at first sight it may seem that this is the fact. Illuminated surfaces are plain surfaces and have two dimensions, but the Moore tube has only one dimension, so to speak. The diffusion is perfect in one direction and very imperfect in the other direction. Place a pencil between a piece of paper and the light, with the pencil parallel to the tube, and there results a relatively dense shadow. Place the pencil crosswise and there will be no shadow at all. This shows the failure to diffuse across the tube.

It is even possible with incandescent lamps distributed over the ceiling to get a more perfect diffusion than with the Moore tube. The discontinuity added by the use of incandescent units in the direction of the length of the tube is not as important in disturbing uniform distribution as the large gaps between the tubes in the other direction. Dr. Pupin with his "load-coils", which he used in telephone circuits, found that a few, perhaps seven or eight coils per wave length, had nearly the same effect as distributed inductance and capacity.

Furthermore, I cannot agree that daylight necessarily produces the best spectrum. This a matter purely of experiment and experience. If the eliminating of the red or the violet from daylight is found to make an improved light to work by for any particular purpose, it is then better to suppress the red or the violet rays. I believe for many purposes that this suppression is advantageous.

There are a few more statements that perhaps require challenging. Mr. Moore says:

> It is now impossible to state definitely what their final life will be, beyond the general statement that some of these tubes have already been in operation over 4000 hours without change, and that there are good reasons for believing that they should continue to run at least as long again, which is a much longer life than any other form of illuminant yet invented.

If he will take pains to inquire, he can find out a great many places where commercial tubes of the Cooper-Hewitt type have operated for 10,000 hours; in this I am speaking of commercial installations.

He also says:

> It is the blinding brilliancy of the mercury tube that makes even a direct glance at it so very harmful to the eye.

I wish to state here that this statement, the equivalent of stating that the mercury vapor lamp is very harmful to the eye, is diametrically opposed to my own experience with this type of lamp.

Mr. Moore disposes very summarily of the new types of incandescent lamps, but perhaps they can take care of themselves.

In regard to Fig. 8 of the paper, Mr. Moore has taken a number of stations at different points in a room and determined the intensity of illumination at each, and then averaged the results. These points are well chosen to determine the intensity of the illumination at different locations, but it is not fair to average these values as they are taken, to get the average illumination, because some of them represent a very much smaller area than others. The proper way to obtain such an average is to divide the surface into a number of equal units, determine the illumination of each unit, and average these.

Though Mr. Moore's mercury valve for supplying gas regularly is very ingenious, yet I question its reliability if the lamp is left unused for a considerable time. Mercury-sealed valves while practically tight for a short time are not usually so indefinitely; after a while the mercury absorbs a little air on the surface exposed to the atmosphere and delivers it by diffusion on the vacuum surface. Once the tube leaks sufficient air, by being out of commission for a month's time perhaps, it would not start up again.

Some difficulties, I imagine, will be found; for example, the great inconvenience of a failure. This room, for instance, is entirely dependent on each particular part of the tube; any crack or damage done to the tube in any part will put the room in darkness. Furthermore, repair is not a matter of taking a spare tube out of the closet and putting it up. Dependance must be placed upon the manufacturer. The organization of a well-disciplined "trouble force" can eliminate some of the trouble, but in many cases it will be found a serious handicap. The power-factor seems to be a variable question. If the power-factor is made very high it means the elimination to that extent of the resistance or inductance backing which absorbs voltage, and will allow more variation in the current which might become a serious factor. Where power is bought from a lighting company and paid for by meter, a low power-factor is not serious because only the drop in the wiring needs consideration; but for those who do their own lighting the capacity of the generator must be considerably greater for a low power-factor load to get a given quantity of energy than with the high power-factor. This will be an added charge against the Moore tube in cases where the power is used largely for supplying these tubes.

With the whole illumination dependent on one or two or three outfits, it is impossible to light a small portion of a room only. In a factory two men who are working in a corner cannot light that corner only, but must perhaps use ten or twenty times as much energy as otherwise would be required. This objection cannot be urged against the Moore tube in all places; it simply shows a certain limitation when the broad field is considered.

Summarizing: it is a little too soon to tell what the commercial field of the Moore tube will be; undoubtedly there is a field for such a light.

Its good points are its relatively high efficiency (not the best, but relatively good—probably better than most carbon incandescent lamps), its even diffusion, and the fact that it has no bright spots and requires very few outlets.

Clayton H. Sharp: I think we all greatly admire the persistency of purpose and the courage with which Mr. Moore has tackled and has kept tackling for ten or fifteen years this great problem of the production of artificial light by the incandescence or luminescence of gases. Certainly the goal toward which he was striving, and the end which he sought to reach, was a most tempting one. We have all heard a great deal about the low efficiency of all of our ordinary illuminants; very few of them approach five per cent. luminous efficiency. Some of them may reach the value of 10% possibly, but most of them are perhaps of only two or three per cent. luminous efficiency. It certainly is a very attractive problem, that of producing an illuminant working at a luminous efficiency of 90% instead of 5%. I think we all regret sincerely that, judging by present indications, in his endeavor to reach this worthy goal Mr. Moore has failed. He has, however, succeeded in producing a practical illuminant which will undoubtedly find a field for itself in certain applications and which has an efficiency that brings it on a par with many of the other illuminants of the present day.

Mr. Moore says that the watts per hefner of the yellow tube vary from 1.3 to 2.5 watts per hefner-candle; or, in other words, from 1.5 to 2.9 watts per candle measured at right angles to the tube. The white tube, the carbon dioxide tube, has a lower efficiency, but no data are given on the watts per candle of the white tube. However, we may arrive at a value by comparing the conclusions drawn from two of the illumination tables which Mr. Moore gives: we find in this way that the white efficiency bears a ratio to the yellow efficiency of 1.5 to 2.9, or about 1 to 2. In other words, the yellow tube is about twice as efficient as the white tube. I do not think we can lay much weight on these comparisons, since, as Mr. Moore himself has stated, all comparisons of illuminants made by taking illumination values under certain specific conditions, are practically valueless as general criteria for the illuminants themselves. However, taking this comparison, we find that the watts per candle of the white tube would range from 3 to 3.8. The yellow tube, according to this, shows an increase in efficiency over the carbon-filament lamp, but this increase is by no means revolutionary. On the other hand, its efficiency, according to these data, is considerably less than that of the tungsten lamp. Consequently we can say in a general way that the Moore light does not represent an essential gain as compared with the other illuminants at the present time. If, therefore, it is to find a place as a practical illuminant, it must show certain other advantages which the illuminants with which it competes do not possess.

What are some of the advantages? It gives a diffused light, that is perfectly true; it is a light of low intrinsic brilliancy, it has no bright spots to blind the eye; it does away with a certain amount of wiring in the building. What are some of the disadvantages. I think some of us might say that the color of it is not all that it should be; it may be the color of daylight, but it is a peculiar kind of daylight; it has the great disadvantage of not being divisible, we throw a switch and turn on all the light into a room; we cannot have a little light here or there, as we need it. This point was brought out by Mr. Thomas. This indivisibility of the Moore light makes it necessary, it seems to me, in all or nearly all of the installations where it is used, to supplement it by some other system of lighting which has the feature of divisibility. It would hardly do, it seems to me, to place all the reliance for the lighting of a room of any importance whatever on a tube of this kind, for we know something about the fragility of glass. I do not think that we can consider the tube to be absolutely immune from breakage, and if it breaks we are in the sad position of being obliged to call in, not the ordinary plumber, but the glass plumber. The glass plumber may be available if we have our installation within a proper distance from the factory, but this feature would be a very disadvantageous one in any installation which is at a distance from these special glass-plumbing facilities.

Another serious disadvantage, noticed here to-night, is the flickering due to the alternating current. This is an exclusively alternating-current lamp at the present time, and when it is used on alternating current of a commercial frequency, such as this, we notice a very marked flickering on objects moved quickly in the light. In cases where the objects have to be handled with rapidity this would be a serious practical disadvantage. In any room where the objects are moved rapidly the effect produced could be scarcely called anything less than weird; unless it is possible to overcome this disadvantage in some practical way, and it is hard to see how this is possible, we must mark this down as a serious detriment to this style of lighting.

Another result of the indivisibility of the lighting is its inapplicability to localized lighting. Diffused and distributed lighting such as we have in this hall is excellent for many purposes, but we do not want it for all purposes. Where localized lighting is desired rather than distributed lighting; the economical illumination of certain portions of a room rather than uniform illumination of the whole room; we must use something which is capable of division, and the Moore tube would appear to be ruled out in such cases.

Let me say one word regarding illuminometer comparisons of various illuminants. This method is undoubtedly excellent for many purposes. If we have a certain room that we wish to illuminate, and if we could carry out illuminometer tests with the various kinds of lighting appliances that are available, we could determine the best system for lighting that room, but unfortunately research of this kind is something which cannot be carried out except under very special conditions. Ordinarily the matter of illuminating a certain space has to be given into the hands of an illuminating engineer who must work with such data as are available, and from the results of experience he has had in similar installations, to choose the kind of illuminant he considers best for the purpose and install it to the best advantage he knows how. As Mr. Moore said, comparisons of illuminations made under certain specific conditions are generally worthless for the purpose of generalization. We need to be able to generalize. We should know how much light a certain source will emit with a given amount of energy. In order to do this we have to study the source itself and determine its total flux of light per watt. This does not mean a test of the illumination in a certain specified room, 40 by 80 feet, but a study of the source of light itself. Without wishing to depreciate the value of illumination tests—for illumination tests I thoroughly believe in—I do not think we could accept the general validity of results that would be obtained under certain specific conditions, in showing the availability or non-availability of all sources of light. In that connection I wish also to raise my voice in deprecation of the term "watts per hefner" and "hefner-foot". It is bad enough to have the "candle-foot", because the candle-foot ought to mean the product of the candle-power by the feet, but it does not mean that. When we lug in an extraneous unit of light which is represented by a most excellent standard of light; namely, the Hefner Alteneck amyl acetate lamp, but which is not practically recognized as a unit in this country, we are going far astray and getting badly mixed up in our units of measurements. If Mr. Moore had used the hefner-metre in measuring the illumination I should have less quarrel with him because the metre and the hefner go together. The hefner knows nothing about the foot, and the foot does not know much about the hefner.

Another statement should be challenged, and that is that the average watts per candle of incandescent lights used in the city of New York is in the neighborhood of five. By a comparison such as one can make from a casual investigation of incandescent lighting in New York and London, I am inclined to think that perhaps the figure of five watts per candle might apply to the lighting in London, but I do not think that it applies to New York conditions.

John W. Howell: I am not going to say anything about incandescent lights. It has been my pleasure to know Mr. Moore and to know his work during the entire 12 years he has been working on this vacuum tube. At first he showed us a small Geissler tube, and for a long time afterward it was a simple Geissler tube, and when everybody thought that Mr. Moore was chasing rainbows he stuck to his work with a persistence, courage, and enthusiasm which I have never seen equalled. The light which we see to-night is a development from the Geissler tube, and it has been accomplished only by this most persistent work, the progress having been made little by little, step by step, never any very long steps until quite lately. He has at last produced a commercial result. As he says, he has added a commercial illuminant to those which the electrical engineer has at his disposal, and one which has a good many uses in which it excels others.

There may be things in Mr. Moore's paper to criticise. I could criticise some things which have not been alluded to yet, but I have no mind to do it. My only wish is to congratulate Mr. Moore on his work.

Among the uses to which Mr. Moore applies his light the first he names is art galleries. My friend, Dr. Berliner, has just remarked to me that there are many art galleries in Europe which are open only during daylight hours because there is no illuminant safe enough to be trusted in those galleries. I think this light would be admirable for such work, because there is no possible danger, except possibly in installing it. If this light could be once installed, the public could have the use of the galleries for much longer hours and with perfect safety.

Leon Gaster: The researches made in obtaining light from gaseous conductors within glass tubes form a decided advance in the conversion of electric energy into light. Bearing in mind however, the progress recently made with the manufacture of incandescent lamps by the use of metal filaments like tantalum osmium, tungsten, zirconium, titanium, etc., or alloys of those metals, with some of which efficiencies are now obtained of about one watt per candle, the practical application of gaseous conductors is somewhat reduced. The great advantage claimed of obtaining properly diffused illumination by the use of the Moore vacuum tube system, can now, to a very large extent, be obtained by the use of the more modern lamps, in combination with proper shades, globes, and reflectors, and by a judicious distribution of the lamps. There is no doubt that a vast field still remains open for the application of this gaseous tube method of illumination.

Will Mr. Moore kindly say whether he has had an opportunity of studying the effect the pink, yellow, etc., colors have upon the eyes because for the present there seems to be a great difference of opinion as to what the ultimate effect upon sight will be, by the permanent use of such illuminants as the Moore or Cooper Hewitt types. I should venture to suggest that the illuminating engineers should conveniently have such an investigation carried out, contributing thereby to settle the prejudices and objections which are raised against the use of such types of illuminants. Facts and data gathered from unbiased investigators would form a valuable guide to those who have to advise in these important matters.

Gano Dunn: I am in sympathy with what Mr. Howell has said about the work of Mr. Moore. It is an example of persistence that has seldom been exhibited before. We have known Mr. Moore as harping on his light for so many years that he has become a symbol of the persistent inventor. I am not forgetting to-night, as we are taking the easy course of looking backward upon his work, how very different the forward look was during all the years when we longed for the day when we should have cold light. I was Tesla's assistant at the famous lecture he delivered on cold light at extremely high frequencies; I know of other work in that direction that has failed before and since; I know how we all dreamed of the day when the secret of the fire-fly should be revealed and we should have sticks of cold light where-ever we wanted them. Those sticks of cold light we actually see around us in this room. They represent the accomplishment of an ideal the engineering and scientific world has long been struggling for.

I venture to comment on that criticism of Mr. Moore's paper, advocating photometric efficiency measurements as the only proper comparison of illuminants, by saying that we have a right to take a practical view. Here we are sitting in a room with three alternative systems of illumination at command. Readings which I was permitted to observe just before the meeting, show that when the illumination comes from the ordinary source of lights behind the cove, 10 kilowatts of electrical energy are required. When the illumination comes from the naked lights strung around the border, five kilowatts are required, and when the illumination comes from the tube, four kilowatts. It is obvious to every one of the two hundred members present that the tube consumes less energy and gives a brighter light than either of the other sources. This is a practical fact that no discussion of photometry or brilliancy or efficiency can do away with, and we should give Mr. Moore credit for having accomplished it.

D. McFarlan Moore: I am asked how much gas enters the tube and how often it has to be replenished. The paper states that some tubes have already run about 18 months, corresponding to about 4000 hours, without replenishing. The paper states also that any tube can be replenished, that is, the phosphorous bottle can be replenished, at a neglible cost, so that this tube light is unlike other lights to the extent that the life of the tube itself is practically unlimited because it does not blacken. I am asked what vacuum gauge I referred to. It is a new vacuum gauge, which I developed for this particular work. I did not go into a description of it because the paper is long enough and I wish to reserve that together with a number of other subjects for future papers. I am also asked why does not the air enter the tube when the light is out. Mr. Thomas referred to this matter and doubted the ability of a mercury seal to hold the vacuum indefinitely. I know of a number of cases where mercury seals have held perfectly for years. Besides such a valve can be fixed very easily in case there should be any leakage.

Practically all Mr. Steinmetz' criticisms will be found to be answered in the paper. There is one thing that will not be found in the paper and that is a criticism of the illuminating engineers who installed the other systems of lighting which were compared with the tube; in fact they need to be commended, not condemned. The highest talent in the country was procured for the lighting of this splendid hall and the incandescent lighting is done well in all respects. The same can be said in reference to the arc lamps that were compared with the tube. The paper shows the location of these arc lamps, and I am sure that the majority of illuminating engineers would agree that it would be a very difficult problem to locate these arc lamps in any more desirable or advantageous positions than they were located in, in the basement where they were supplanted by the tubes. So with the location of the incandescent lamps in the lobby of the well-known theater, which is one of the tests referred to. These lamps are installed in the regular orthodox fashion; that is, in long rows. Fig. 8 shows that they are located in the best possible manner. The solution of the diffusion problem, when using the incandescent lamp system, is to place them as we have them in this room; viz. 92 separate machines in a row to accomplish a certain result which can now be better obtained by one machine, a plain simple tube.

This system of lighting undeniably differs radically from all of the old style systems. It is self-evident that the light diffused from such a large tube more nearly imitates daylight than any illumination that could possibly be obtained from any intense-point source. I maintain that man cannot do better than try to imitate daylight. No form of light will probably imitate it absoluely, but it should be our endeavor to imitate it as closely as we possibly can. Fortunately, it so happens that simple carbon dioxide comes closer to an exact imitation of average daylight color values when used in a vacuum tube than any other form of light. Its superior color values place it in a class by itself. The most delicate shades of colors have been matched under the tube when it is producing the pure white light due to $c\,o_2$. You will note that the 16-ft. tube on the platform which early in the evening gave a 30 hefner per foot light when using nitrogen is gradually changing to a pure white light because it is now adjusted to feed itself $c\,o_2$. The tube lighting this room is being feed with nitrogen and therefore a yellow light results which is the color that gives the greatest efficiency. According to the laws of nature, about twice as much energy is required to develop the necessary wave lengths for a white light, that is, to produce a spectrum that closely corresponds with daylight, than is required for yellow light which has a maximum effect upon the human eye.

The length of life of the tube has been referred to. I said that 8000 hours would be longer than any other form of illuminant—I refer to thoroughly commercial forms of illuminants—and then also assumed the illuminant to be still in perfect condition at the end of the test. It is true that some mercury tubes have had a long life, but at anything like the end of an 8000-hour run a mercury tube is far from clean. This tube will remain at the same degree of transparency for an indefinite period of time, and therefore the maintenance cost for long tube lighting is exceedingly low. My statement about the brilliancy of the mercury light was carefully made. I said a direct glance at the mercury tube. Judging from personal experience, I again state that the mercury tube is harmful to the eye if one looks directly at it. Mercury tubes seem to be efficient in terms of watts per candle-power but a number of them could not light this room as efficiently as this long tube does, to say nothing of the mercury tubes prohibitive color. The matter of breakage has also been mentioned. In all matters of engineering it is well to have duplicate units, and therefore large areas are now provided for by equipping them with a number of tubes so that the absence of lights from one tube will be comparable to the going out of an arc lamp or several arc lamps. Such large areas as department stores, for example, can now be perfectly lighted without an inch of wire within their walls.

Fears were expressed that these tubes could not withstand temperature changes without serious difficulties arising due to expansion and contraction of the glass, but practice has proved such trouble to be practically nil and therefore this system is applicable to street lighting. A continuous line of tubing can extend directly above the curb or be supported from the buildings to illuminate the show windows, sidewalks, and streets with a perfectly distributed light.

The best answer to the discussion on power-factors is to state the cold fact that this tube is now operating at this moment at a 75% power factor. Dr. Sharp and Mr. Steinmetz referred to thematter of efficiency and also spoke of the spherical candle-power of the tube. The curves in the paper show the watts per hefner obtained by horizontal measurement of a portion of the tube. I prefer the hefner after having had years of practical experience in trying to use other so-called standards of light. A committee of this Institute after a thorough investigation has recommended the hefner lamp. So far as divisibility is concerned, that is, having lights in small units, much can be said, but I will simply refer you to Fig. 15.

The images of moving objects have been referred to. It is true that a higher frequency is advantageous to a tube of this kind. For a number of years I investigated various methods for overcoming these images; I succeeded to a great extent, but found when I put the tubes on the market that the images were not an important factor at all. Of the two miles of tubing in use to-night there has not been a single practical commercial objection raised on this question. In this connection it should be noted that all who have actually worked under the light speak of its softness and the absence of any eye-strain whatever. Even in machine shops, where it was anticipated the movement of the lathes would be important, turned out to be negligible. On frequencies higher than 60 cycles per minute this trouble disappears entirely, at least so far as the average eye is concerned.

In reference to the tests proposed in a room 40 by 80 ft., I still most decidedly believe that such a method is the only practical solution of the problem of obtaining true commercial relative values of the various forms of light. I said that local conditions must be stated in every test of this kind, but of course I am assuming the local conditions to remain constant for any series of tests on different lights. This room, for example, has a neutral color and uniform fittings, and therefore each light would have a fair opportunity to do its best if the tests were made as directed in the paper. I believe it is the duty of all electrical organizations to aid in every way possible to standardize all forms of light, and I do not think this can be accomplished until a room such as I have described has been equipped, and I believe in the interest of science such a room should be established at some convenient place.

The following data were obtained by comparative illumination tests made in this assembly room of the Engineer's Building this afternoon between the Moore tube lighting system and the regularly installed concealed incandescent lamp system and the temporary rectangle formed by rows of exposed incandescent lamps which is the same size as the rectangle formed by the Moore tube.

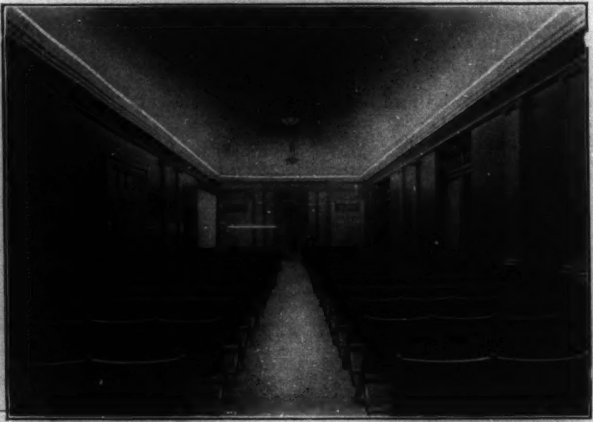


FIG. 1—Assembly room No 2, Engineers' Building, illuminated by the Moore tube light

In these tests a portable illuminometer was used to measure the intensity of the illumination in hefner-feet at nine stations and at a uniform height of 35 in. from the floor.

The Moore tube is made of clear glass and is located as shown in Fig. 1. It is 176 ft. long and forms a rectangle 62.5 by 25.5 ft. It is 1.75 in. in diameter and is not provided with a reflector of any kind. This tube is automatically feeding itself nitrogen, therefore the color of its light is about the same as that of incandescent lamps. Horizontal photometric tests on a portion of the tube 0.5 in. long showed the tube to require 1.6 watts per hefner from the 60-cycle street mains. It was operating at 14.8 hefners per foot, or a total of 2600 hefners.

The tube having only been recently installed has run only some 25 hours and has not reached its final efficiency, which will be 1.4 watts per hefner after about a 50-hour run and thereafter it will maintain this efficiency indefinitely.

The concealed incandescent lamp system. The tubular 8-c-p. 119-volt incandescent lamps are located behind the cove as shown by the detailed drawing of Fig. 1. A two-way socket is located every 16 in. therefore 288 lamps are in use. Immediately behind each lamp there is a reflector. The lamps and entire equipment is new, having only been used a very few hours. Equally spaced on the longitudinal center line of the ceiling of the room are located 3 incandescent clusters which are concealed by opalescent reflectors each containing 6 lamps of 25 candle-power.

The exposed incandescent lamp system. The temporary circuit of incandescent lamps is installed to parallel the tube throughout its length. It is therefore located close to the tube, between the tube and the edge of the cove so that all of the lamps are exposed and not shielded in any way. They are all new 3.5-watt 117-volt incandescent lamps. They are spaced 24 in. apart, and therefore 90 are in use. Each lamp is in a vertical position.

MEASUREMENTS OF ILLUMINATION.

Engineers' Building, Assembly Room No. 2.

Hefner-feet.

Station	Moore tube system	Concealed incandescent system	Exposed incandescent system
1	4.72	1.72	2.67
2	3.67	2.83	2.37
3	2.90	1.90	2.31
4	2.83	2.40	1.89
5	3.14	1.98	2.07
6	3.83	1.83	2.31
7	4.40	1.61	3.85
8	3.66	1.90	2.47
9	4.90	1.77	2.37
Mean illumination (Average hefner-feet)	3.68	1.99	2.48
Power-factor	75%	1	1
Area square feet	1930.	1930.	1930.
Watts per Square feet	2.15	5.31	2.62
Volts	225.	118.	119.
Amperes	24.5	86.4	42.4
Watts total	4150.	10250.	5050.
Illuminating efficiency $\left(\frac{\text{Mean hefner-foot}}{\text{Watts per square foot}}\right)$	1.71	0.375	0.95

CONCLUSION

1. That the Moore tube lighting system has 4.6 times the illuminating efficiency of the concealed incandescent lamp system as installed under these local conditions. The Moore tube produces 85% more useful illumination, yet requires 60% less wattage than the incandescent lamp system. This test emphasizes the inefficiency of concealed lighting, and in many cases where the light of incandescent lamps is used to penetrate opalescent skylights an exposed tube can produce an equivalent effect for about one-tenth the power.

2. That the tube produces 57% more useful illumination, yet requires 18% less wattage. Under average commercial conditions this tube would have shown its superiority over exposed incandescent lamps on the basis of 2 to 1. It was noted that the intrinsic brilliancy of the exposed incandescent lamps was too great, but not so that of the tube.

The following tables show the results of the tests that have been made this evening, while this meeting has been in progress. The illumination readings for each of the three systems have been taken at stations Nos. 2, 3 and 4, Figs. 1 and 2.

For convenience in comparison, a table of the readings on the same three stations is abstracted from the complet test made this afternoon.

MEASUREMENTS OF ILLUMINATION.

Engineers' Building Assembly Room No. 2.

Tests made previous to meeting. Hefner-feet.

Station	Moore tube system	Concealed incandescent system	Exposed incandescent system
1.			
2.	3.67	2.83	2.37
3.	2.90	1.90	2.31
4.	2.83	2.40	1.89
5			
6			
7.			
8.			
9.			
Mean illumination (Average hefner-feet)	3.13	2.38	2.19
Power-factor	75%	100%	100%
Area square feet	1930.	1930.	1930.
Watts per square feet	2.15	5.31	2.62
Volts	225.	118.	119.
Amperes	24.5	86.4	42.4
Watts total	4150.	10250.	5050.
Illuminating efficiency $\left(\frac{\text{Mean hefner-foot}}{\text{Watts per square Foot}}\right)$	1.45	.45	.84

MEASUREMENTS OF ILLUMINATIONS.

Engineers' Building, Assembly Room No. 2.

Tests during meeting. Hefner-feet.

Station	Moore tube system.	Concealed incandescent system.	Exposed incandescent system.
1			
2	3.2	2.7	1.44
3	2.72	2.7	1.11
4	2.33	3.8	1.22
5			
6			
7			
8			
9			
Mean illumination (Average hefner-feet.)	2.75	2.97	1.25
Power-factor	72%	1	1
Area square feet	1930.	1930.	193 .
Watts per square feet	1.97	5.61	2.41
Volts	228.	119.	117.
Amperes	23.	91.	40.6
Watts total	3800.	10840.	4650.
Illuminating efficiency $\left(\frac{\text{Mean hefner-foot}}{\text{Watts per square foot.}}\right)$	1.4	0.52	0.52

It will be noted that the "illuminating efficiencies" agree closely with this afternoon's test of the tube system and the concealed incandescent system. The exposed incandescent system is, however, 61% lower because in this afternoon's test the volts were higher than the rated voltage of the lamps. This serves to illustrate forcibly a well known characteristic of the incandescent lamp; that is, their rapid falling off in efficiency with a drop of voltage, for it will be noticed in the first test the volts were 119 as against 117 in the second. The latter being the rated voltage of the lamps, represents the true efficiency based on these three stations. Moreover, since the same ratio would hold for all stations, the illuminating efficiency 0.95 given in the complete test should be 0.6, which would make the tube system about three times more efficient than the exposed incandescent system in this particular case, and after the end of 50 hours' run when the tube will have an efficiency of 1.4 watts per hefner the ratio will be 1 to 3.4. Finally, after 500 hours run, when the average efficiency of the incandescents will be about 4.5 watts per hefner, the tube would show an illuminating efficiency over four times that of the exposed incandescent lamps.

It will also be noted that neither a similar change in the tube voltage nor a considerable change in the tube watts due to adjustment of the gas valve has materially altered its illuminating efficiency.

The complete test covers symmetrically one quarter of the room, which is also symmetrical, and therefore represents accurately the average illumination of each system. Therefore a room of this kind can be lighted by the Moore tube for one-fourth the cost at which it can be done by incandescent lamps. Similar comparative tests with all other commercial lights will prove the long tube the most desirable. However, there is no cause for alarm, because the adoption of the tube must be gradual and the commercial field is so great that there is plenty of room for all forms of illuminants, each of which will continue to occupy its own particular field. The efficiency race between gas and electricity has always been keen, but I believe the tube has placed electricity in the lead once more.

Reference has been made to art galleries. I will merely add that in order to grasp the spirit of a painting it should always be viewed under the same quality of light it was executed under; namely, daylight. Therefore, the picture should be viewed in the closest imitation of daylight possible and this can be done by using plain carbon dioxide in a vacuum tube.

Mr. Gaster referred to the color problem, and asked as its effect on the human eye. The paper answers that question. The light that comes nearest to the natural light is the one that is best. The nearer we approach to daylight the further away we shall be from doing injury to the eye. There are three factors of importance in connection with injury to the eye so far as light is concerned: color, intensity, and steadiness. The object should be to generate a light at such a low intensity that it can be used in its initiative condition and final condition; that is, without the need of shades, etc. The incandescent lamps or any of the point sources of light need shades either to soften the light or to reflect it, or diffuse it or tone down its color. With the tube method we can decide before we make the lamp just what color we need and obtain it by using the proper gases. I wish to refer to a remark I first made about 10 years ago, namely, that I believe the most important scientific advances of the near future would in one way or another be connected with the vacuum tube. The theory and facts I have presented to-night will, I think, sustain this contention.

Clayton H. Sharp (by letter): In considering the color of the tube with which this hall is lighted, attention should be called to a well marked phenomenon, which doubtless all of you have noticed and which to my mind is very significant. We have seen that when the incandescent lamps are turned on after the Moore light has been in use for so long a time that we no longer find its color particularly strange—the incandescent lights have a very decidedly greenish hue. Their light looks very much like that from an old style incandescent gas mantle when the latter is viewed in comparison with an incandescent lamp. Now we know from actual spectro-photometric measurements that the old style incandescent gas mantle does contain an excess of green in its spectrum, and we know also that this is most distinctly not the case with the light from an incandescent lamp. The spectrum of the latter light is continuous and approximates very closely to the spectrum of an absolutely black body; that is to say, all colors are emitted with equal facility. How then do we account for the fact that this light looks greenish when viewed by eyes which have grown accustomed to the color of the Moore tube? It seems to me that the explanation is to be sought by a consideration of some of the simple facts of physiological optics. The green sensation which we get on looking at the light of the incandescent lamp is a color contrast effect. It is produced by the influence on the eye of long exposure to a light which contains an excess of red. In other words, the continuous exposure to the excessive red of the Moore tube causes a temporary red blindness due to retinal fatigue. Under these circumstances any light containing a normal amount of all the colors will necessarily appear strongly tinged with green. It should be noted, therefore, that the green which is seen is not actually in the incandescent light itself, but is a subjective phenomenon induced by the unnatural color of the vacuum tube light. This state of affairs opens up at once a wide field for speculation and experiment on the possibility of more permanent and perhaps harmful effects being produced upon the eye if the Moore tube were used habitually as an artificial illuminant. The advocates of the mercury-vapor light claim that a greenish-hue light is best for the eyes as far as fatigue is concerned, and that red is harmful. If this claim is founded on fact, the light from this Moore tube must suffer greatly by comparison with the light from the mercury-vapor tube. But is this claim well founded? Do we know what hue a light must have in order to make it best for the eyes? We have frequently had expressions of individual opinions on these matters, but as far as I know no thorough-going investigation of our variously colored sources of light to determine what hue a light should possess to enable work to be done by it with the minimum of fatigue has ever been carried out and published in such a way as to furnish practical engineering data on this most important subject. With the widely ranging hues which the illuminants of the present day exhibit, this problem has a significance which was absent fifteen years ago, when particolored illuminants were unknown, and it seems to me that the time has come when it ought to be attacked by illuminating engineers and by oculists working in coöperation with each other.

R. A. Fessenden (by letter): A member of the Institute has good reason to be proud of the achievements of his fellow members in considering the history of electric lighting. At the beginning we have the incandescent lamp of Edison and the arc lamps of Thomson and Brush; at the present time it is to members of this Institute that the world is indebted for the most efficient developments in the four great classes of electrical illuminating devices. These are:

1. The point incandescence source, represented by the helion lamp of Messrs. W. G. Clark and H. C. Parker.

2. The point arc source represented by the magnetite lamp of Doctor Steinmetz.

3. The tube vapor source represented by the Cooper-Hewitt mercury lamp.

4. The tube gas source represented by the Moore lamp.

It is always unsafe to put a limit to developments in any particular line, but I am inclined to the opinion that these four types will not be greatly improved upon and will remain the standard methods of illumination until they are supplanted by some purely chemical means as suggested by Professor Elihu Thomson. This is not likely, however, for a good many years.

The various other types of lamps such as the tantalum, osram, osmium, tungsten, graphitized filament, calcium arc, Nernst lamp, etc., must I think all be considered as transition apparatus.

The labor and energy spent in devising these types of lamps is not, however, wasted. The development of the metallic-filament lamps, for example, has placed within our hands new methods of obtaining the rarer metals in workable form, and, as in the case of tantalum and osmium, has furnished us with new materials which are bound, sooner or later, to be of use in other lines.

It will be noted that the efficiency of all these types of lamps is in the neighborhood of one watt per candle, and I am inclined to think that by no method in which the light is produced by electricity will this efficiency be much exceeded, except possibly from a monochromatic source.

Mr. Moore's paper must be considered definitely to mark the beginning of a new era in electric lighting. Now for the first time we have a source of electric light which is not intrinsically brilliant and does not need to be shaded or diffused. Also for the first time a uniformly distributed illumination can efficiently be obtained.

Some doubts have been expressed as to the accuracy of Mr. Moore's measurements, but the objections are based upon lack of knowledge of the elementary principles of photometry. It is too self-evident to require argument that a much higher uniform intensity of illumination will be obtained with the same amount of energy from a distributed source than from a localized one.

With reference to the efficiency of the Moore lamp, this agrees almost exactly with some measurements made by me and published in 1901*

Of vacuum tube lamps, many have been suggested. It must be nearly thirty years ago that the first attempt was made to light a mine with vacuum tubes and induction coils. Since then we have had many types, as, for example, Crookes cathode bombardment lamp, and others

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*"Light without Heat," *Electrical World and Engineer*, January 5th, 1901:

which, surrounded by a cloud of non-luminous verbosity, have not done much actual illuminating. The only approach to success, of which the writer is aware, is the admirable work of Macfarlan Moore. I know of no reason why his lamp should not ultimately prove a success for certain classes of work, where very long tubes and high potentials are not objectionable. In 1890 I made measurements on the efficiency of vacuum tube illumination, by passing the current a certain time, measuring the candle power of the tube, due to the light from the gas, and then dropping the whole tube into the water. (I was fonder of glass blowing then than I am now.) From the energy put in, (for an ammeter I used a hot wire voltmeter, with silver instead of platinum; this is a good instrument for such work) the heating of the water, and the candle power, the efficiency was determined. It came out quite high, *slightly less than* 1 *watt per candle power*. Most of the loss was found to be in the heating of the anode and cathode, and this it was attempted to overcome in two ways. First by lengthening the tube, which gave good results, though not commercial, and secondly by making the gas itself the secondary of a transformer. This failed because of too great hysteresis loss in the iron, though one type was not so unpromising.

Some question has been raised as to the commercial future of the Moore lamp. I do not agree with those who hold that its use will be a limited one. While the introduction of any new system is always more or less slow, I believe that in the not far future the greater part of the interior light load of city stations will consist of Moore lamps. The construction of the Moore lamp is especially suited for the coming types of concrete building architecture, and were I an architect I should not consider the lighting of any public hall or lodge room by any other means than a Moore lamp. While it would not pay to alter the present method of lighting the auditorium of the Engineers' Building, I would suggest that it might be worth while ascertaining whether the Moore light could not be advantageously used in lighting the library and some of the halls of the building.

At the same time that we admire the results obtained and the ingenious means by which they are accomplished, we can not help but extend our admiration to the pluck and perseverance with which Mr. Moore and those associated with him have worked on in the face of apparently insurmountable difficulties until they have now finally reached I believe the point of commercial success. It has sometimes occurred to me that much more courage is sometimes shown in financial undertakings than in actual warfare.

A paper presented at a meeting of the Boston Branch of the American Institute of Electrical Engineers, Boston, Mass., May 15, 1907.

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AN ANALYSIS OF THE DISTRIBUTION LOSSES IN A LARGE CENTRAL STATION SYSTEM

BY L. L. ELDEN

The central station system under consideration is typical of those in service throughout the country, serving the larger centers of population and including adjacent suburban districts within a radius of upwards of fifty miles from the main generating station.

This system, as is the case with many similar systems, comprises the business of a number of companies that have been amalgamated into one large organization. This larger organization, with its greater financial resources and highly trained administrative and engineering forces, has naturally proved better fitted to meet the demands for service arising from an area of 450 square miles, in which thirty cities and towns, having a population of 1,000,000 persons, are served by the system.

Of the 1800 miles of streets included in the territory, 750 miles are covered by the lines of the system, which extend 43 miles in a single direction from the generating station. The total 50-watt equivalents connected to the system aggregate 1,600,000, equal to 80,000 kilowatts. This load comprises the usual mixture of power, heating, and lighting apparatus which constitute the business of a central station system. The maximum demand is approximately 44% of the connected load at the time of the yearly maximum, and approximately 27% during the average days of the year. These two results are indicated by Fig. 1, which shows the average load curves of the system for the maximum and average days of the year 1906.

The generating equipment consists of two main generating stations, one generating three-phase, 60-cycle alternating current exclusively, and the other generating low-tension direct current. In addition there are two small generating plants located at remote parts of the system, which are still in service independent of the main system. When convenient, these will be discontinued as generating stations and converted into substations supplied with current from the main generating station. To facilitate the distribution of current over the large territory, sub-stations are maintained at suitable centres, at which points the high-pressure transmission lines deliver 60-cycle, three-phase, alternating current for conversion to direct current and alternating current at voltages suitable for commercial purposes.

As will appear in some of the tables given later, three transmission pressures are used; namely, 2300 volts, 4600 volts, and 6600 volts. In explanation of the apparent complication of voltages in the transmission system—it was found more convenient and economical to maintain certain installations of underground cables and motor-generators which were acquired in the purchase of another company's plant, than to abandon the large investment represented by such equipment. All new installations are made at 6600 volts, it being the intention gradually to eliminate the lower transmission voltages as conditions may dictate.

Throughout the entire system but three forms of service are supplied for commercial purposes; that is, either low-tension direct current, single- or three-phase alternating current.

The low-tension, direct-current district, representing slightly less than 1% of the total area of the system, is supplied exclusively by three-wire direct-current at 115–230 volts. This is used indiscriminately for power, lighting, and heating service.

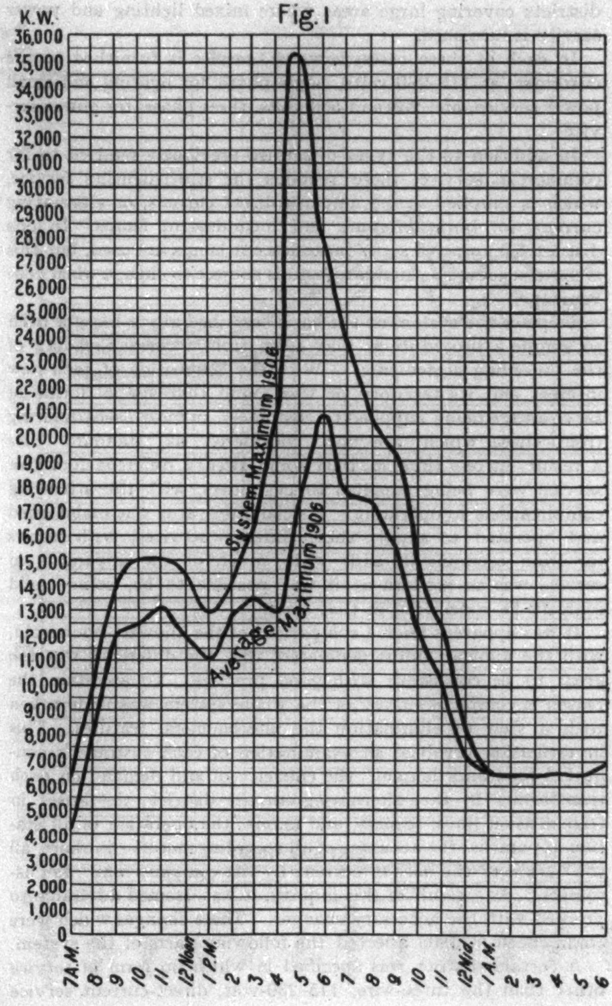
Similarly, the alternating-current district, embracing 99% of the area, is supplied exclusively by the alternating-current system of distribution. Three types of primary distributing circuits are used in the various sub-station districts, according to the demands for service, as follows:

1. 2300-volt, single-phase circuits in resident districts where only lighting and small power service is required.

2. 2300-volt, three-wire, three-phase circuits are used in districts of limited areas where mixed lighting and power service of considerable amounts are to be furnished.

3. 2300-volt, four-wire, three-phase circuits are used in

Fig. 1


K.W.
36,000
35,000
34,000
33,000
32,000
31,000
30,000
29,000
28,000
27,000
26,000
25,000
24,000
23,000
22,000
21,000
20,000
19,000
18,000
17,000
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7000
6,000
5,000
4,000
3,000
2,000
1,000
0
System Maximum 1906
Average Maximum 1906
7 A.M.
8
9
10
11
12 Noon
1 P.M.
2
3
4
5
6
7
8
9
10
11
12 Mid.
1 A.M.
2
3
4
5
6

districts covering large areas where mixed lighting and power service is furnished.

In each of these cases, however, service is furnished to the customers at 115–230 volts, single phase, for lighting and small power service, and 230 and 550 volts, three phase, for power service.

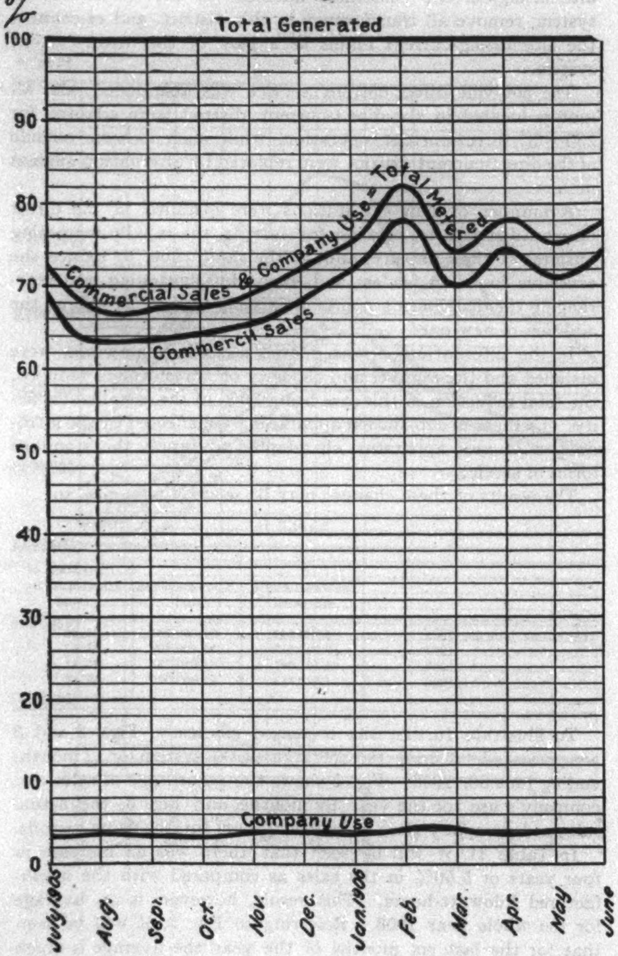
In addition to the types of service previously referred to for commercial service, there remains the street-lighting service, which is supplied at 6.6 amperes direct current, or alternating current, for both series-arc and incandescent lamps. In one district 3.5 amperes series incandescent lamps are used, but this is not considered as standard, and is subject to change when convenient.

To place the system on the basis described above has not been so simple a procedure as may seem from a cursory reading of the preceding statements. With the acquisition of each new interest and its territory, it was found that special forms of service were being supplied to customers, in most cases differing from those which are now considered as standard. As a result, at one time in 1903 some twenty different forms of service were being supplied to customers, with the attending complications in operating. Special apparatus was maintained and operated to supply these different services, with results far from economical; and, while much of the apparatus in service was as modern as it was possible to be, some could scarcely be considered in that class.

It was apparent from a comparison of the kilowatt-hours sold, with the kilowatt-hours generated, that the difference was too great to be consistent with good practice. To ascertain the reason a complete survey of the whole system was undertaken with a view of eliminating the uneconomical features. This investigation involved an examination of each customer's connected load and demand; the capacity of and demand on each transformer in the alternating-current district; the losses in transmission lines, feeders, and mains; the operation of all station apparatus; the accuracy of all recording meters—in short, all the details of the uses of current by the company and its customers. As a result of this inquiry, it was deemed advisable to proceed with the necessary changes. These changes which were commenced in 1903 affected the following parts of the system.

A certain district was specified in which no form of service other than the three-wire, 115–230-volt, direct-current service

Fig. 2


%
Total Generated
100
90
80
70
60
50
40
30
20
10
0
Commercial Sales & Company Use = Total Metered
Commercil Sales
Company Use
July 1905
Aug.
Sept.
Oct.
Nov.
Dec.
Jan. 1906
Feb.
Mar.
Apr.
May
June

would be supplied. This made it necessary to transfer all the alternating-current customers affected, to the direct-current system, remove all transformers in this district, and re-connect the alternating-current mains as a part of the direct-current system.

The 500-volt direct-current service was abandoned, and all motors located in the direct-current district were adapted for 230-volt, direct-current operation, while such as were outside of the direct-current district were replaced by alternating-current motors.

A number of new sub-stations were installed in the direct current districts to provide for serving the rapidly increasing business of the company, and, at the same time, to reduce the excessive losses in feeders and mains by shortening and rearranging the distributing points of existing feeders, as well as the addition of new ones.

In the alternating-current district secondary networks were installed and the number and capacity of transformers reduced, the total reduction in this case being 30% of the installed capacity. Changes in sub-station apparatus were effected by the introduction of new apparatus, all adapted to supply the standard forms of service.

The results of these changes may be seen by reference to

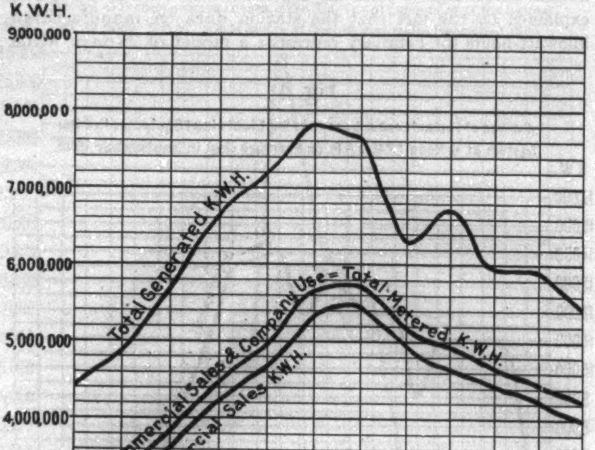
TABLE II.

	Kilowatt-hours generated.	Kilowatt-hours sold.	Percentage of kilowatt-hours sold
Year ending June 30, 1903........	49,122,344	31,569,741	64.26
" " " " 1904........	57,531,315	37,220,199	64.67
" " " " 1905...... ..	64,161,987	41,910,281	65.31
" " " " 1906..	74,582,311	52,003,000	69.82

To illustrate further the increased efficiency, Figs. 2 and 3 are presented, covering the operation of the system for 12 months ending June 30, 1906. Fig. 2 shows the percentage of sales and company's use for the year by months, and Fig. 3, the actual sales and company's use in kilowatt-hours for the same periods.

In Table II, it will be seen that there was an increase in four years of 5.56% in the sales as compared with the manufactured kilowatt-hours. This result, however, is an average for the whole year 1906. Referring to Fig. 2, it will be seen that for the last six months of the year the average is much

Fig. 3

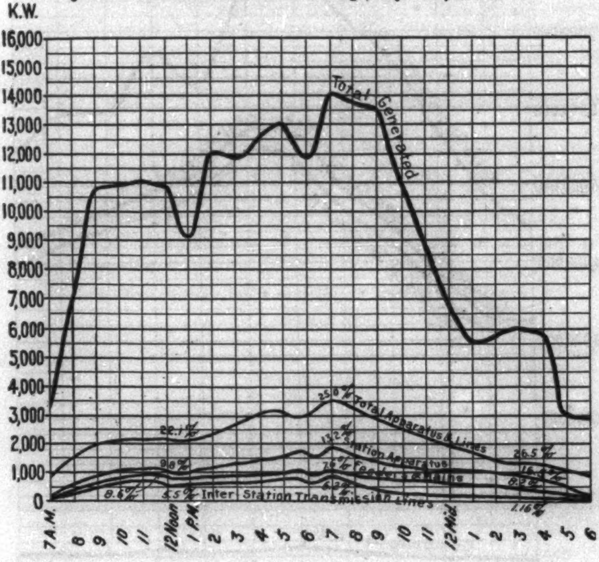

K.W.H.
9,000,000
8,000,000
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Total Generated K.W.H.
Commercial Sales & Company Use = Total Metered K.W.H.
Commercial Sales K.W.H.
Company Use K.W.H.
July 1905
Aug.
Sept.
Oct.
Nov.
Dec.
Jan. 1906
Feb.
Mar.
Apr.
May
June

higher, it being actually 73.65%, this figure indicating future possible results.

It will be noted that the curves in Figs. 2 and 3 show an abnormal percentage of sales for the month of February; this is explained by the fact that the station data on manufactured kilowatt-hours for February represent a month of 28 days, while the total sales represent an average month of 30 days. Other points in these curves which do not coincide may be attributed to the same cause.

Fig. 4

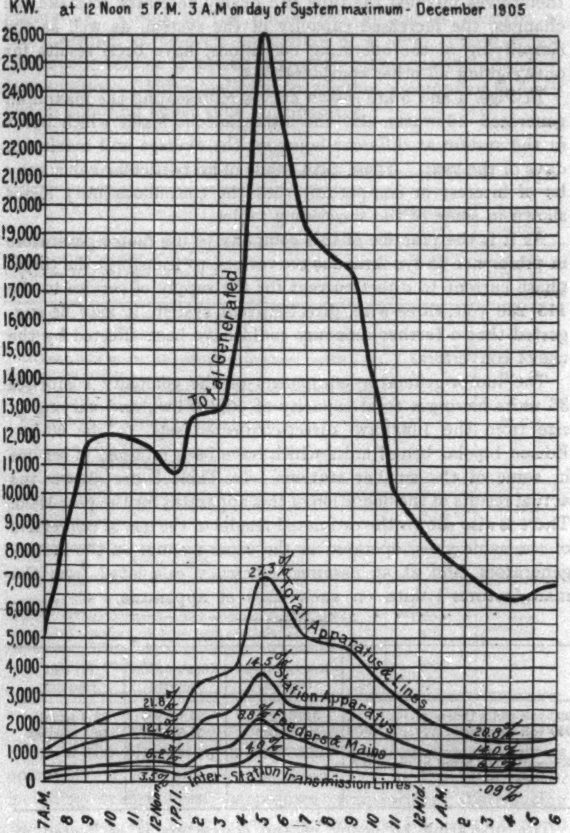
Curves of Instantaneous Losses in the Electrical Equipment of the System at 12 Noon 7 P.M. 3 A.M. on average day in September 1905



Using the data for 1906 as given in Table II as a basis, it will be seen that it would have been necessary to manufacture approximately 5,000,000 kilowatt-hours more in that year to sell the same amount of current, if the conditions had been

Fig. 5

Curves of Instantaneous Losses in the Electrical Equipment of the System at 12 Noon 5 P.M. 3 A.M on day of System maximum - December 1905



the same as existed in 1903. Further, if the average of the last six months of 1906 had been maintained throughout the year, a further saving of 5,000,000 kilowatt-hours would have been made during the year. While the resulting economies have in themselves justified the time and outlay necessary to make the changes, the increased capacity of the system, as well as the simplifying of the operating conditions, have been results far outweighing all other considerations.

In Figs. 4 and 5 are shown curves representing the maximum generated kilowatts, also the instantaneous losses which occur in the system at different hours on the average and maximum days of the year. These data, while of no particular value, may be of interest in comparison with the continuous duty losses shown in some of the succeeding tables.

As it is the practice of this company to use motor-generators in preference to synchronous converters, to transform the three-phase current to direct current for the supply of service to the 115–230 volt, three-wire, direct-current system, it may be suggested that a further economy could have been effected by the use of converters.

The motor-generator equipment of the company comprises 36 units having a total capacity of 10,210 kw., and varying in size from the 1,000-kw. direct-connected sets, to the 60-kw. Edison bipolar belted units which have been retained in service in some of the smaller stations. In Table 3 are shown the actual results of the operation of this apparatus for the year 1906. There is also shown the estimated results of the use of converters of the same sizes, operated in the same manner as the motor-generators, and at an assumed efficiency calculated from the manufacturer's data on such sizes of apparatus.

TABLE III.

	Kilowatt-hours received.	Kilowatt-hours delivered.	Per cent efficiency.
230-volt motor-generator..........	31,331,406	25,803,990	82.4 actual
230-volt converters...............	30,004,639	25,803,990	86. assumed
Kilowatt-hours saved by use of converters......................	1,326,767		

The operating efficiency of the converters is estimated at 87%, less 1% for the current used by the cooling apparatus, while the efficiency of the motor-generators was 82.4%. The table shows a saving of 1,326,767 kilowatt-hours by the use of converters, this representing the premium paid for the use of the more reliable apparatus, in addition to which there is to be added the slightly larger investment necessary in the purchase of motor-generators. Owing to the well-known difficulties incident to the operation of 60-cycle converters in a large system where continuous service is placed above all other considerations, it is a question of individual opinion whether a company is justified in adopting either type of apparatus.

TABLE IV

Comparative data of alternating-current and direct-current systems

	Alternating current	Direct current
Area of system per cent. of total	99.1%	0.9%
Connected load per cent. of total	21. %	79. %
Commercial service, street lighting service omitted		
Total losses from generating stations to customers' meters	41. %	20. %
Efficiency of system	59. %	80. %
Total losses from sub-stations to customers' meters in percentage of current delivered from sub-station	24. %	7.5%
Efficiency of distributing system	76. %	92.5%
Street lighting system		
Total losses from generating stations to street lamps	15.2%	31.9%
Efficiency of system	84.8%	68.1%
General data		
Connected load in kilowatts	17300	62700
Capacity of transformers installed on distributing circuits	10388	——
Capacity of transformers in per cent. of connected load	60%	——
Approximate kilowatt-hours delivered to each system in per cent. of total generated	30%	70%

Table 4 presents some data illustrating the comparative losses in the alternating-current and direct-current systems as operated. In the alternating-current system the total losses, including transmission, step-down transformer, distributing circuit losses, and meter losses, aggregate 41.1%, equivalent to an efficiency of 58.9. Eliminating the losses in transmission lines, step-down transformers, regulators, boosters, etc., the total losses in the distributing circuits, meters, etc., aggregate

24.2% with a resulting efficiency of 75.8% from the sub-station to the customers' meters.

In the direct-current system the total losses, including those in transmission lines, motor-generators, tie-lines, feeders and mains, meters, etc., aggregate 20%, equivalent to a system efficiency of 80%. Eliminating all losses in the direct-current system, except those which occur between the direct-current switchboard in the sub-stations and the customers' meters, a total loss of 7.54% is shown, or an efficiency of 92.46%.

Two forms of street-lighting service are in use, each involving the operation of different types of apparatus. In one case motor-generators are used to convert alternating current to 6.6-ampere series direct current, and in the other case constant-current-transformers are used to obtain the 6.6-ampere series alternating current for similar service.

TABLE V.

Distribution of Current for the Year Ending June 30 1906

	Kilowatt-hours.	Loss in per cent. of total generated kilo-watt-hours	Per cent. of generated Kilowatt-hours transmitted
Commercial sales	52,003,000	69.82	
Company use	2,774,383	3.72	
Total losses	19,270,616	25.87	
Unaccounted for current	441,437	0.59	
Total generated	74,489,436	100.	
Sub-division of Total Losses			
Losses in station apparatus	10,586,117	14.21	16.6
Losses in inter-station transmission lines	2,920,653	3.92	5.92
Losses in feeders and mains	5,763,846	7.74	10.50
Total losses station apparatus and lines	19,270,616	25.87	

The total losses in the 6.6-ampere direct-current system are shown to be 31.9%, giving an efficiency of 68.1%. For similar service from the alternating-current system, the total losses are 15.2% with a resulting operating efficiency of 84.8%.

The methods employed in preparing the data by means of which the losses in the system are determined may be understood by reference to Tables 5, 6, 7, 8, and 9. These tables present a summary of the year's operation. Similar tables are prepared monthly which deal with the shorter period of time.

It should be understood that with the exception of such items in these tables as are preceded by an asterisk, all the data shown are the results of records taken from recording wattmeters. In such items as are excepted, computations were necessary, all of which were made from reliable data furnished by the manufacturer of the apparatus in question, supplemented in many cases by tests made by the company's representatives.

The losses in the individual commercial distributing circuits were determined by the drop-of-potential method, a constant being obtained for each circuit by taking a large number of pressure tests under all conditions of load. The losses in the direct-current mains were estimated in the same manner. The losses in the street-lighting circuits were calculated from the known length of the circuits, and these results further checked by voltage readings at the station while the circuits were in operation with a known number of lamps burning.

TABLE VI

LOSSES IN STATION APPARATUS FOR THE YEAR ENDING JUNE 30, 1906

	Kilowatt-hours	Loss in per cent. of total power generated	Loss in per cent. of input
230-volt motor-generators	5,527,416	7.42	17.6
500-volt motor-generators	373,059	0.50	33.6
Series arc motor-generators	2,403,471	3.22	25.5
Step-down transformers	1,010,848	1.36	3.23
*Constant-current transformers	118,548	0.16	5.40
*Potential regulators	65,353	0.09	3.53
Batteries	807,067	1.09	43.2
Boosters	211,264	0.28	63.0
Balancers	67,725	0.09	
Water rheostats for testing	1,366		
Total	10,586,117	14.21	

Every year the company makes thousands of tests of the meters in use on the customers' premises. For the year 1906 the results of all such tests showed that the average meter error was 2.6% slow. This factor has been used to account in part for some of the unknown losses, the total thus accounted for being approximately 1.5% of the total power generated.

Table 5 shows, in the first part, a summary of the principal

TABLE VII

LOSSES IN INTER-STATION TRANSMISSION LINES FOR THE YEAR ENDING JUNE 30, 1906

	Kilowatt-hours	Loss in per cent. of total power generated	Loss in per cent. of input	Per cent. of total generated power transmitted
Three-phase 2,300-volt lines	1,556,981	2.09	8.41	24.8
Three-phase 4,600-volt lines	98,813	0.132	1.52	8.7
Three-phase 6,600-volt lines	770,577	1.04	3.55	29.1
230-volt direct-current tie-lines	494,282	0.66	18.30	3.6
Total	2,920,653	3.92	5.92	

TABLE VIII

LOSSES IN FEEDERS AND MAINS FOR YEAR ENDING JUNE 30, 1906

	Kilowatt-hours	Loss in per cent. of total power generated	Loss in per cent. of input
*2,300-volt commercial lines	1,854,854	2.50	25.1
230-volt direct-current feeders	1,901,948	2.55	4.93
*230-volt direct-current mains	641,343	.86	2.00
*500-volt direct-current feeders	74,466	0.10	9.15
*Street-lighting circuits	809,103	1.08	9.53
*Meter potential losses	482,132	0.65	
Total	5,763,846	7.74	10.5

TABLE IX

DIVISION OF KILOWATT-HOURS SOLD BY DISTRICTS FOR THE YEAR ENDING JUNE 30, 1906

Station	Per cent. kilowatt-hours received	
1-13	68.9	
14	100.	
15	100.	
16	75.	
17	98.3	
18	63.5	
19	55.4	
20	52.4	
23	55.9	
25	72.8	
	69.8	Total system sales

items without subdivision. The latter part of the table subdivides the total losses in the system into divisions which are treated individually in the later tables.

In Table 6 the losses in station apparatus are subdivided and distributed among the various pieces of apparatus used in the operation of the stations.

Table 7 indicates the losses in the inter-station transmission lines.

Table 8 shows similar data on feeders and mains.

Table 9 shows the percentage of sales in each sub-station district as compared with the current delivered to that district for distribution. In explanation of this table, it should be noted that stations 1 to 13 include the direct-current district and a portion of the alternating-current district. Stations 14, 15, and 17 represent stations to which current is sold wholesale, to be redistributed by the local companies controlling these districts. Stations 16, 19, 20, and 23 represent sub-stations, each of which distributes service to one or more cities or towns in the suburban districts. Stations 18 and 25 represent small generating stations which are still in service in two of the recently acquired suburban districts.

In making comparisons of the several districts, some of the individual characteristics of each district should be understood. Station 16 supplies a district where large amounts of power are used, also a large amount of street-lighting service. Station 18 supplies a district similar to 16, except that the amounts of power and street lighting service are relatively less.

Stations 19, 20, 23, and 25 supply service to districts covering large areas where resident lighting and a moderate amount of street lighting are the only uses made of the service.

The preparation of these data involves the labor of one man for a period of approximately one week each month. It is his duty to watch the operation of the system through the statistics furnished him by the operating and sales departments, comparing them with data which have been prepared representing the possible maximum conditions of efficiency of operation of every piece of apparatus and reporting for investigation any divergence from the estimated average operating losses. The curves, which are prepared monthly, show the percentage of losses in the current handled by each motor-generator, storage-battery, balancer, booster, exciter, step-down transformer, constant-current transformers, or any other station apparatus, thereby providing means for immediately detecting any unusual results, and furnishing an invaluable check on the operation.

Aside from the value which these data may have from an operating point of view, it is of considerable interest in indicating the characteristics of each district as a revenue producer, thus making it possible to judge accurately of the advisability of making extensions for the different classes of service.

If there should be undertaken at this time the construction of a generating and distributing system similar to the one under consideration, the installation would be made under conditions which would eliminate the disadvantages encountered in reconstructing existing equipments, as in the present case. This would be particularly true in certain parts of the country, where the limitations placed by the local authorities on permissible operating conditions are less severe, and where the quality and the continuity of the service are not of such paramount importance,—all such conditions tending to greater economy and reduction of operating losses than is possible in the present system.

A paper presented at the 219th Meeting of the American Institute of Electrical Engineers, New York May 21, 1907.

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SOME FACTS AND PROBLEMS BEARING ON ELECTRIC TRUNK-LINE OPERATION.

BY FRANK J. SPRAGUE.

Certain memorable opinions, recently uttered by railroad men whose creative and administrative work, and wide experience entitle them to preeminence, command attention. In March last, the New York *Times* contained an interview with Mr. E. H. Harriman, who discussed at length various features of the present steam railroad situation; the influence of national and state legislation; the developments, needs, and present difficulties of operation; and the vital necessity of increase of capacity, measured in its broadest terms. Expressing his individual opinion that perhaps it might be better, considered from the standpoint of the steam locomotive, if a wider gauge than the present standard had originally been adopted, he went on to say:

> But perhaps it is chimerical to think now of rebuilding the railroads of the entire country, and of replacing the entire railroad equipment. If so, what is the best thing? Obviously, electricity. And I believe that the railroads will have to come to that, not only to get a larger unit of motor power and of distributing it over the train load, but on account of fuel. That brings up another phase of the existing conditions. We have to use up fuel to carry our fuel, and there are certain limitations here just as much as there are in car capacity or motive power, particularly when you consider the distribution of the coal producing regions with respect to the major avenues of traffic. The great saving resulting from the use of electricity is apparent, quite aside from the matter of increasing the tractive power and the train load. * * * * * * *
>
> The only relief which can be obtained through economies of physical operation must come through the outlay of enormous amounts of money such as would be involved in a general electrification or a change in gauge.

At the April meeting of the Buffalo Chamber of Commerce, Mr. W. C. Brown, senior vice-president of the New York Central Lines, likewise comprehensively discussed the present railway situation, and the influence of legislation and management upon credit, pointing out the " appalling blow to that credit," not so much because " of what has been done, as the manner and temper with which it has been done, and the fear of what may follow." The pressure upon the railroads, the imperative and continuing need of development and improvements, and the limitations in available capital—all were specially emphasized by this statement:

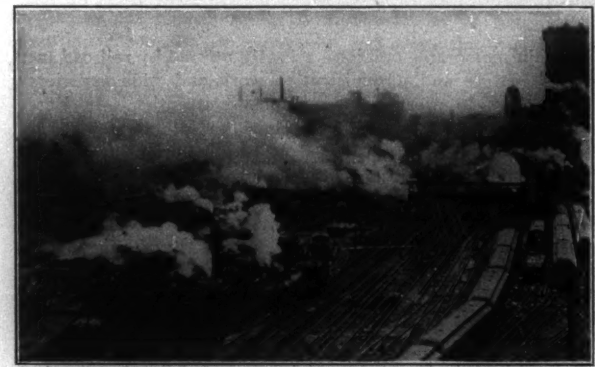


FIG. 1—Section of present steam terminal, New York Central.

> If the development and expansion of the nation is to go on, if the progress made during the last ten years may be accepted as in any respect a measure of progress to be made during the coming decade, almost as much money will have to be expended in increasing the facilities of existing railroads, and in building additional railroads, as has been expended during the eighty years since the beginning of the construction of railroads in the United States.

These opinions are confirmatory of that of Mr. James J. Hill, who some time ago startled the investing world by his estimate of a billion dollar annual expenditure, now actually confirmed by detailed estimates.

Coming from such high sources, from men who are fitted by nature and experience to survey the whole field with special clarity of vision, and to summarize their conclusions with extraordinary judgment these utterances are pregnant with meaning; for coupled with the remainder of their remarks, they tell us that if there is the proper coöperation between the national and state governments and the railroad corporations, a permanently established confidence between the public and those who serve it, based upon integrity of management and equity of treatment, and a reasonably surety of a fair return on money invested—all absolutely necessary to command the confidence of capital—then, in spite of temporary setbacks or trade reactions, this country has entered on an era of unequalled expansion, and when planning for future developments the steam railroads must keep in view the possibility of a change in motive power, and the adoption to an increasing extent of the use of electricity is some form.

But it is especially to be noted that while fuel economy, not only in the matter of power generation, but also as affected by its own transportation (often a most serious matter), must be kept in view, the keynote of the prophecies of the future is more specifically sounded in the word *capacity*. It is this fact which must be always borne in mind.

Increase of capacity, not only such as is possible and individual to electric application, but also such as is common to the larger developments of railroads, however operated, means of course economy in its highest sense, that is, saving in passenger and ton-mile operation, assuming that traffic increases at least in proportion to capital account, because of increased loads, reduced train crews, higher operating schedules, better distributed service, less dead time on sidings, less interruptions to schedule and greater freedom from accidents.

I believe that this question of capacity will be a far greater controlling factor in the electrification of trunk-lines than that of economy as narrowly measured by the cost of electrical horse power. I do not know of a single instance in which electricity has been adopted in which this feature has not been paramount, nor do I know of a road operated to-day which would sacrifice capacity to economy.

How much has been actually spent in steam railroad development, to which I assume Mr. Brown's reference is confined, it is impossible to tell, but that it is a stupendous amount, giving some suggestion of future capital demands, is evidenced by the fact that the total of the outstanding stock, bonds, and other obligations of the steam railroads in the United States now aggregates about $13,800,000,000; while similar obligations of the electric railroads, which began their commercial expansion with the signing of the Richmond contract almost twenty years ago to-day, exceed $3,500,000,000.

These are indeed stupendous totals, and when confronted with the possibilities of the future we may well be hopeful, while we ask: Along what lines will this great development naturally proceed? What improvements must necessarily take precedence? How shall the continuing expenditure of capital be conducted so as to safeguard a dividend on it?

We electrical engineers are ambitious, fairly courageous, and given to prophecy. We have much warrant for it, and every reason to be proud of what has been accomplished in an unmatched industrial progress; but we are a little apt to be prejudiced in favor of our own work, and perhaps somewhat partisan in promoting it. I think we often lack in large measure the familiar knowledge of railroad finance and operation that is necessary in dealing with the larger railroad problems, in order to insure our fairly weighing the importance and value of all the elements which must be considered.

Such, at least, is apparently the opinion of the friendly, but yet mildly sarcastic and somewhat pessimistic editor of the *Railroad Gazette*, who, referring to the recent meeting of the Institute of Electrical Engineers on the occasion of the presentation by Messrs. Stillwell and Putnam of their paper on the substitution of the electric motor for the steam locomotive, remarks:

> The pity about the meeting referred to is that there was no speaker there who knew as much about the practical requirements of railroading as he and the others did about the advantages and economies of electric propulsion.

This is quite likely true, for most people know a little more about their specialty than about the details of every business collaterally connected with it. But, really, the electrical engineers of the country, many of them professional civil and mechanical engineers as well, are not entirely destitute of a knowledge of both steam and electric operating conditions, nor can they all fairly be classed as a lot of unthinking enthusiasts; their knowledge and experience amount in the aggregate to a very respectable total.

But we must not take our genial critic too seriously, nor be over-much discouraged by his limitations of vision, for his is not the only publication that has trailed after accomplished facts in the electrical world, nor his the only voice that has been raised in doubtful protest on the eve of great developments. Heed, however, must be taken of the fact that trunk-line operation is in many respects a very different thing from that of urban or interurban railways, and the attempt to introduce electricity into steam railroad operation must observe in the fullest measure these differences. We can, therefore, take the criticisms made of us in good nature, and I think win the proper support of steam railroad men, and come nearer to the successful introduction of electricity where justified, by setting forth with entire frankness the facts as they have been, are, and promise to be, and avoiding too strenuous and arbitrary prophecies of what must be. You will note that I do not except myself from this generalization, and therefore I trust my engineer confrères will not deem me lacking in impartiality in formulating this gentle criticism.

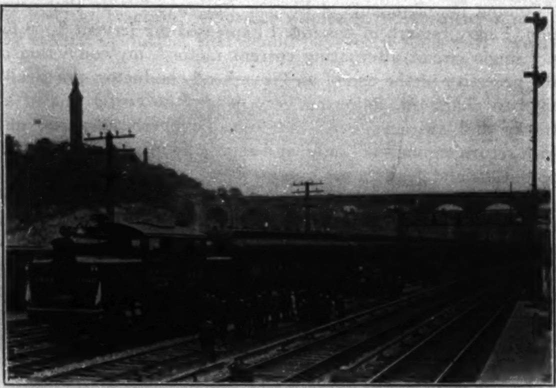


Fig. 2—First New York Central electric train, September 30, 1906. Leaving High Bridge for Grand Central Station.

Many of my hearers are young in years, and some of them just starting in railroad experience. Many statements made to-day may therefore have an air of novelty, but there are certain fundamental truths referring to the electric equipment of steam-operated trunk lines which have always, since the beginning of this development, been broadly true. I have stated them time and again during the last twenty years, and in a score of publications. I cannot state them any more fully now, but inasmuch as they are expressive of my present as well as past beliefs, and having been made at various times may now in part be lost sight of, I take the liberty of referring to them in an appendix to this paper, and I will briefly summarize a few extracts.

Fifteen years ago, in Chicago, I had the honor, as president of this Institute, to make my inaugural address on the subject: "Coming Developments of Electric Railways." On that occasion, I may remark in passing, I expressed my fervent hope for a "single circuit alternating current motor," my conviction of the necessity of the use of an "overhead conductor, practically rigid in character, following very nearly the center line of all tracks and switches, with no movable overhead parts, and with return through the rail," and especially my belief in higher potentials and gearless motors.

My attitude on the broad question of trunk-line operation was then the same as it has consistently been since, for it has not been altered by more intimate contact with the trunk-line development. It may be briefly summarized in the simple statement that, taken as a whole the electrical equipment and operation of trunk lines is essentially more of a financial than a technical problem. It is certainly not solvable by ingenious methods of bookkeeping, or transmission of burdens to posterity. In that address I said

> Any predictions which are made concerning the future of electric propulsion, either in ignorance or disregard of the possibilities of steam duty, and the limitations necessarily existing in all systems of transportation, deserve and will receive little consideration from those charged with the responsibilities of conducting our great railway system, for unless passengers and goods can be moved over a system with increased benefit to a community, or at a reduced cost, or with a commensurate return on capital invested, an electric will not replace a steam system.

The commercial success of electric operation is a question of relative and absolute density of train movement.

> It narrows itself down to the one question as to the number of trains operated between the two terminal points. Make that number of trains sufficiently large, and the electric motor is the best means of electric propulsion Decrease this number, and steam is to be preferred.

In closing that address, after pointing out the difficulties surrounding trunk-line operation, and the electric developments which it seemed to me would take place, I added:

> Temper your enthusiasm with prudence; limit your attempts to the solution of those problems which will prove of practical benefit. Do not chase rainbows, but seek lessened costs of operation for equivalent duty and increased return on invested capital.
>
> All this is said in no spirit of discouragement, for I yield to no man in my confidence in the future of electric traction. No new field is so rich, none more pregnant with great possibilities.

Where do we find ourselves to-day? Has there been any essential change in the essential governing facts?

Two years ago, we celebrated, and very rightly, the "Triumph of Electric Traction,"—not the wholesale replacement of steam by electric operation, that would have been somewhat premature—but the magnificent results which had been achieved. A new industry had been created, affording investment for thousands of millions of capital, and employment for hundreds of thousands of men. Time, distance, and mountain elevations had been abbreviated, great vistas opened up, barren spaces peopled, new homes created, towns linked to each other and to their neighboring cities, and animal drudgery relieved. Direct-current, single-phase, and polyphase equipments were in operation; and a new system of power aggregation and control, the multiple unit, had solved elevated and underground problems, and made possible enormous concentration of capacity. The power and speed of the heaviest steam locomotives had been equalled or surpassed, and some of our great trunk lines had contracted

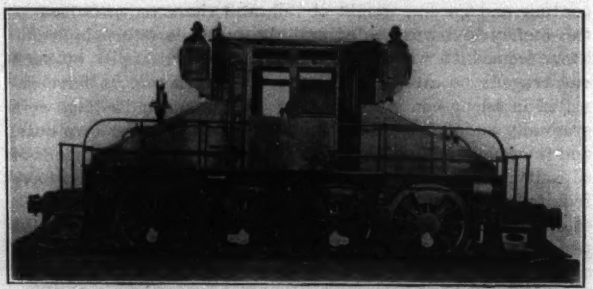


Fig. 3—Early Sprague, Duncan, and Hutchinson—1000 h. p. electric locomotive.

for improvements costing over a hundred millions of dollars, made possible only because of the availability of electricity. But again referring to the broad question of trunk line operation, I felt impelled, even in that hour of elation, to say:

> What, then, will determine the future? Solely the financial factor, as it must the future of any other great industrial problem. When savings in operation and the increased returns from traffic on any road will more than pay a fair dividend on money invested for electrical equipment then, and then only will trunk lines, great or small, be operated electrically. As I have often stated, the problem resolves itself into a question of relative density and the character of load-factor, and these essentials are of course vitally connected with the allowed working potential.

Let us consider for a moment the evolution of the steam railroad. As a rule, it has started with a single track, with such contour and grades, weight of rail, and character of ballast as the money to be expended and the probable return in traffic have seemed to warrant, and generally handicapped by such extravagant or attempted profits in construction as have resulted in a long-continuing burden. Turn-outs and sidings were gradually supplemented by more sidings and longer turn-outs, and then such short sections of double tracking as the demands of capacity, traffic, schedule, and commercial conditions have required or permitted. Then there came a time, on many a road, of receivership, followed by reorganization and an extended period of recuperation; or if not receivership, then a long time of nursing into a condition of reasonable commercial health. As the demands of capacity increased, there followed the introduction of, or improvement in signal systems, additions to rolling stock, increases in the number and capacity of locomotives, until the road found itself with an equipment of extraordinary variety of varying conditions of efficiency; meanwhile, intermingled with a part of its own were all kinds of freight equipment from roads throughout the country. Through service for freight, express, passenger and sleeping cars, and terminal connections with other roads marked the transition from a road of more or less local to one of "through" character, The new relationship made an increasing demand on capacity. and double tracking became essential for a part, or perhaps for the whole of the route; and with this new demand likewise the necessity, oftentimes carried out beforehand, of some relocation of tracks, changes in alignment, reduction in grades, improvement in ballast, abolition of the more serious grade-crossings, especially near terminal cities, and extensions and improvements in, and enlargement of terminals and freight yards.

Now every one of these developments has been dictated primarily by one requirement—increase of capacity. This is the keynote of all railroad development, however rated, for it makes possible an increase of revenue miles of freight or passenger traffic which can be carried on a given trackage or operative mileage of road, and results in a net comparative economy of cost per ton of freight or passenger moved. These improvements are all vital, no matter what the motive power, and they should ordinarily and naturally precede the application of electric power, for it is absolutely certain, except in specific instances, that if these have not been made before the use of electricity is considered, they must be taken up in connection with its introduction.

Here, as during the whole period of growth, the financial question is always present, ever dominant. There probably never was an official charged with the maintenance and operation of a railroad who could not see opportunities for judicious expenditure of capital, and whose requirements have not generally been greater than would be acceded to by the directors and stockholders of his road. On the other hand, it is probably rarely the case that those same directors and stockholders have not wished that the demands made upon them for capital were less than the actual demands, even where granted. The practical question, then, which confronts every railroad is how best can such capital as can be raised on reasonable conditions—which conditions are always variable, and sometimes appallingly oppressive—be expended to meet the actual requirements of the road and to get the largest net return.

The enormous cost of railroad developments has necessarily in a large measure been first met out of the profits of operation, because of the difficulty of raising additional money on account of early extravagances in capitalization, expenditure, and management. Much of this cost often never appears in capital account, but in the end additions thereto must naturally and very properly be made to replace in some degree the amounts diverted from revenue.

In spite of many gross examples of railroad dishonesty, and many unfounded charges affecting railroad officials, it is but proper to repeat a statement made privately a short time ago by one of the best known of the higher railroad officials in this country, a man who has grown up from the ranks and is now in a position that commands the universal respect and esteem of all who know him, that, certainly within recent years, for every thousand dollars which has been added to capital account many thousands have been put into road and equipment from earnings that has never so appeared.

Electricity is no panacea for railroad ills, any more than freight and passenger rates arbitrarily determined without regard to cost of service is a panacea for the body politic. I know of no business in which universal averages as a guide for individual decision can be more unfortunately applied; and this is equally true, no matter what branch of the railroad business is considered. Statistics covering the operation of all the roads in the country may demonstrate to the mind of the mathematician that if all the power used were supplied electrically from central stations instead of by steam locomotives, there would be an enormous saving in cost of power, and therefore electricity should be adopted, no matter what the other demands for capital, or what the net result of an equal expenditure in other directions might accomplish. Such a comparison would, if anything, seem to mean that on those roads where traffic is congested, and where the demand of power per mile of road is not only large in the aggregate but on the average, considerations of power economy should be much more in-

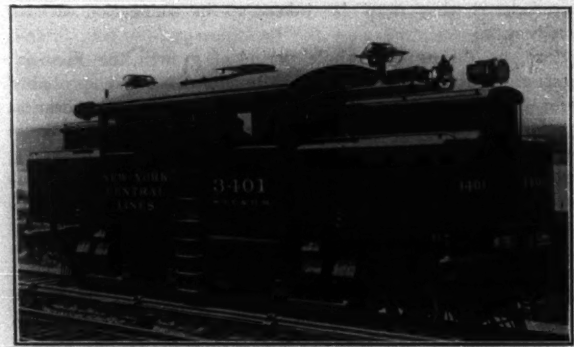


FIG. 4—New York Central 2200 h. p. direct-current electric locomotive.

fluential; but they distinctly do not afford the slightest reason for assuming that the possible saving in power is of sufficient importance to lead to general consideration of electric operation on extended lines with sparse traffic, no matter what systems may be developed.

This criticism, if it may be so called, was objected to on the score that railroads of this latter class, while not properly present subjects for electrification, were changing their character, and that in time the density of traffic would be sufficient to warrant such adoption. This is precisely the point of my criticism. There are roads which can now properly consider the adoption of electricity. There are others which by no stretch of imagination can seriously consider it for many years to come, and the only time when they can do so will be when, by growth of traffic, development in the character of their equipment, and augumentation in financial strength they shall have arrived in the first rank of railroads. Why then dilute whatever advantages there are in the matter of economy—all of which are needed on even the best railroads—by consideration of such as are plainly out of present reach of electric equipment?

In discussing the subject of electrification of trunk lines, there is a tendency sometimes to ignore the varying conditions on the roads, and also the changes in methods of operation which the introduction of electricity may make possible. The railroads seem to be often regarded as systems which must be conducted very much on present lines, that is, operated with locomotive-drawn trains. In order to come to any clear decision, on many roads at least, this conception must be changed. There is no hard and fast rule of classification. A trunk line may generally be considered as a system joining important terminal cities, over which is conducted all kinds of traffic, through and local, passenger, express and freight, and, in the larger systems, a heavy suburban passenger service. The divisions and character of service of course vary widely, but the constant tendency is towards an increasing density of traffic, multiplication of tracks, and extension of the limits of local and suburban services.

When taking up the question of the adoption of electricity, railway officials are met at the outset by an unfortunate and confusing condition of affairs, largely due to manufacturing rivalries, individual partisanship, professional dicta, and gratuitous advice. These are in no small measure responsible for an apparent division of the engineering world into two camps, alternating and direct current, as in the earlier days of electric lighting, a division which it seems to me is entirely unnecessary and misleading.

At a recent meeting of the New York Railroad Club, the argument was advanced by one speaker that the general question of the adoption of electricity should be determined by a railroad quite independently of any details, and that systems, equipment, and methods of operation could then be safely determined. With this view I wish to dissent. A change of motive power involving vast expenditures of money and radical changes in methods of operation, cannot safely be determined upon except after presentation of a comprehensive report, and a general plan of equipment and operation based upon an investigation of previous practice, present or pending developments, and an analysis of important features and details. And this seems all the more essential, for at the present time the technical press is filled, and the public ear vociferously afflicted, with the rival claims of the advocates of direct- and alternating-current systems; the merits and defects of single-phase, polyphase, and direct-current motors; and the beauties and ugliness, the danger and safety of various types of overhead and third-rail constructions. High and low potentials, 15- and 25-cycle frequencies, gearless and geared motors, and air and electric

Fig. 5—Group of eighteen 2200 h. p. electric locomotives.

controls—all are actively exploited. Detail costs and economies, new methods of finance and bookkeeping, and changes in railroad operation and management are presented to the bewildered railroad man with enthusiastic confidence.

But above the discordant notes, and in the turmoil of varied developments there arises now and then the cry of standardization, not only such as is natural and not prohibitive of new advances in the art, but wholesale, explicit, and exclusive. For example, in a recent paper before this Institute, the view was expressed that but a single plan—the high-tension overhead trolley, with 15-cycle single-phase alternating-current motors—was possible of serious consideration on trunk line service, and that this system should now be adopted and standardized, despite the fact that there was not in existence a single equipment of this character in practical railway operation!

I do not intend to burden this paper with statistics, or abstruse mathematics—one can prove almost anything by them —but just here I will epitomize certain conclusions which I think will bear the test of time.

1. Of the two broad lines on which electrification can be considered, if increased economy, that is, reduction of operative expenses by replacing the steam locomotive with an electric one, with concentration of prime power and perhaps the use of water power, be deemed the dominant reason for change of motive power, then every wheel in an electrified division should be turned electrically; and the savings affected should pay not only a fair rate of depreciation of the total equipment, but a satisfactory rate of interest on the new capital expended, in fact a better rate than if spent in some other way.

2. Increase of capacity, both in locomotive haulage, schedule speeds, motor-car trains and terminal facilities, of a character impossible to steam service—all resulting in augmented traffic, and increased use and capacity of the dead part of the systems, the tracks and roadbed—will ordinarily be the more potent influence in leading to the adoption of electric operation, and will often warrant heavy capital expenditures.

3. Every large road is a problem which must be considered financially and technically on its own merits, and in most features other than those which without effort can be harmonized its decision will be of little practical concern to other roads.

4. The adoption of electricity will ordinarily begin with those divisions where traffic is comparatively dense, and once

adopted the territory over which it can be extended will naturally increase.

5. Terminal properties in great cities, underground and tunnel sections, and heavy mountain sections where duplication of tracks because of extra heavy construction cost is prohibitive offer an immediate field for the serious consideration of electrification.

6. There cannot now be safely established any final standard, or any single system selected as the best for all roads. What is the best for one might easily be less advantageous for another, and there is no valid reason why any road should adopt something fitting to a less degree its particular requirements because of the action of some foreign road.

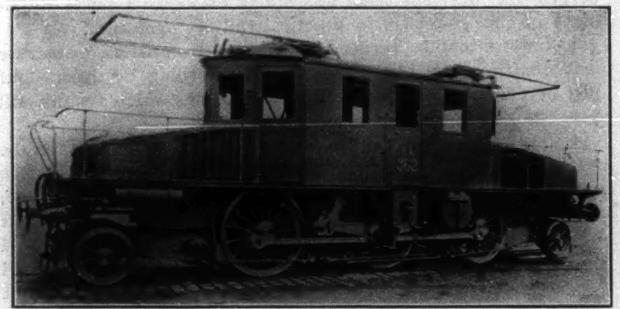


FIG. 6—Ganz 1500 h.p. polyphase electric locomotive.

7. Extraordinary advances have been, and are being made, and new discoveries are always possible. The limits of none of the systems now in use are clearly defined, and it would seem both natural and wise that the various manufacturing, technical, and inventive activities should pursue every lead to its logical conclusion, for the best will be none too good.

It is not my intention in the present paper to investigate railroad economies, or to formulate any final conclusions in the matter of steam railway electrification, but rather briefly to analyze, and make running comment upon various phases of the problem often discussed by engineers; to give some comparative facts as they have thus far developed; to describe sundry developments in electric locomotive construction; and to illustrate in some detail features specifically characteristic of the three typical initial equipments now commanding attention.

Motor equipments. In discussing the selection of any system, the first thing to investigate is the motor. In railway operation that which is to be replaced is a steam locomotive, in other words, a motor supplied by a local boiler, furnace, and coal-bin: that which is proposed in its place is another motor, or group of motors supplied through a wire by bigger boilers, furnaces, and coal-bins, or by energy from a water power. The working conductor, with everything connected to it in transmission or generation, although essential, is tributary to the motor and its requirements.

It is not sufficient that the source of power can be made of any desired size, although it is an essential feature; in any case such concentrated generating equipment must supply a number of motors. What *is* essential, and in the last analysis vital, is that the new motor shall have not only certain mechanical advantages, to the extent of eliminating the evils of reciprocating parts and reducing the cost of up-keep, but above all it must have capacity, measured not alone by drawbar pull or speed, but by both, and it must be of sustained character; and this capacity, to accomplish more than the steam locomotive, must be greater than that of the latter. Such capacity should naturally be attained, first, by increase of the capacity of the individual motor or locomotive, and then, when this increase has reached its limit, by combining motors or locomotives under a common control by the multiple-unit system.

Limitation of design. The designing of electric railway apparatus is handicapped by certain physical limitations which it is not in the power of the designer to change; for example, gauge of track, size and number of drivers, length of rigid wheel-base, dead and total weights per wheel and axle, clearance of motors above the track, permissible speeds of parts, provision for accessibility and repairs, and capacity for heat radiation. Every steam locomotive, when properly designed, has capacity to slip its drivers on sanded tracks, and it can maintain nearly its maximum average drawbar pull for a considerable range of speed as long as its boilers can make sufficient steam. Although at the disadvantage of having reciprocating parts, its drivers being coupled together cannot slip individually. In short, it is designed of a weight necessary to get the tractive effort required to pull a definite load, and then for all the capacity in the matter of speed which its fire-box and boilers can provide for. Essential defects are that its drawbar pull varies widely, depending on the position of the connecting-rod, that it does not materially increase below a certain speed, and the steaming power is limited. Hence comes the limitation of the "ruling grade."

On the other hand, the electric locomotive, when likewise properly designed, provides a drawbar pull of constant character throughout the revolution of the driver, it increases to an extraordinary degree when necessary, and the capacity of the boiler supplied at the central station is ample. On all service, however, high *continuous* capacity of the motor is essential.

Capacity being, therefore, the keynote of the equipment, I shall discuss at some length the characteristics of conductors and motors used with direct current and with alternating current. In so far as these comments relate to single-phase alternating-current operation, they will in some measure be based upon the only existing commercial development of this character now in the United States, that is, upon the series-wound, commutating, single-phase motor with compensated fields, operated at 25 cycles.

Lowering the number of cycles to increase the capacity of the single-phase motor, as has been suggested although not yet developed in commercial practice, of course merits serious consideration, and I shall add some comments upon this proposed change.

Behavior of conductors. Both motors and conductors when used for direct current or for single-phase alternating current, present certain differences of such inherent character that there seems no present likelihood of material change; and this conclusion is as sound in regard to the motor-differences as it is in regard to conductors.

When used for single-phase alternating currents, conductors offer, by reason of self-induction, an impedance or resistance to current materially greater than they present to direct currents. This impedance, and the consequent loss of energy at any particular potential delivery, depends upon the shape and material of the conductor, upon the frequency of alternation, the density of current and the power-factor. Under ordinary conditions, a round copper conductor of, say, No. 0000 size, has at 25 cycles an impedance of about 1.6. But with iron or steel conductors this impedance is increased many times, because the magnetization of the iron and the self-induction drive the current toward the skin of the conductor, so that the body of it is useless, and it might as well be a shell of very much less weight.

This effect in steel rails increases with the quality and with the cross-section of the rail. For example, according to the report of the Test Commission of the recent International Electrical Congress, on 50-lb. traffic rails the ratio of impedance to direct-current resistance at 25 cycles and 300 amperes is about 5.4, while on 80-lb., rail this ratio with the same current is 9.0, with the curious result that increasing the cross-section of the rail does not apparently increase its actual capacity for carrying single-phase currents. Quite the contrary, of course, is the fact in regard to direct currents, the conductivity increasing with the cross-section and quality.

These statements are made not because of special novelty, but in emphasizing certain inherent differences in conductors in their behavior toward the two kinds of current additional weight is lent to the statement that the differences inherent in direct-current and single-phase alternating-current motors are likewise radical, and are probably permanent in character.

Types of motor. Among the many types of motors proposed for railway service, four are now being exploited:

Polyphase alternating-current motor
Single-phase " " repulsion type
" " " series type
Direct-current "

Of these, two, the direct-current and the three-phase motors, each have a continuous rate of energy-input, while the single-phase motor has an intermittent and variable rate. Moreover, there is combined in the single-phase motor two distinct functions, those of a motor and a transformer, and the latter cannot be entirely eliminated. The result is a reduction in both continuous and overload capacities.

It is in this particular that the single-phase motor, despite a great amount of experimental development, has remained defective; and while not prohibitive to the extent of making it an unworkable machine, its defects are so inherent as to place it at a serious disadvantage in individual comparison with other types of motors. To attain the preeminence hoped for, the external advantages in current supply must be very marked. In fact, rated in the same manner and under like physical conditions, it is only about half as good as the direct-current motor. Or to put it another way, the weight of the complete single-phase electrical equipment on a car or locomotive, including transformers, motors, and controlling apparatus, for continuous hard service, and with like physical limitations and ventilation, is about twice that required for direct-current apparatus. In addition to this there is, of course, a material increase in the mechanical equipment necessary to carry the electrical apparatus. The reason is simple—it is because of the heat generated on account of lower electrical efficiency, and the working the fields of the motors at a reduced magnetic flux.

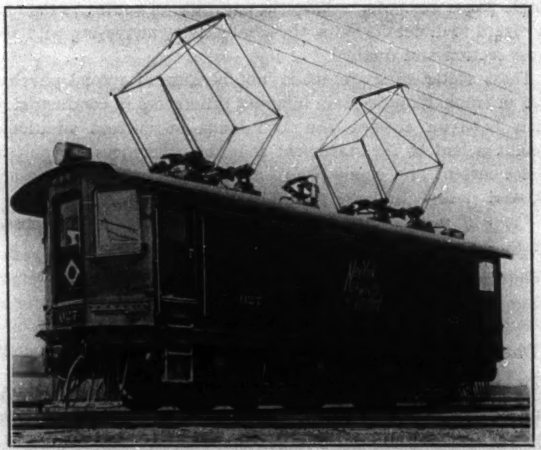


FIG. 7—New Haven 1000 h.p. alternating-current electric locomotive.

When considering locomotives, the net result is that the total weight of a single-phase alternating-current locomotive, with a service capacity equal to that of a direct-current locomotive of like armature speeds and permissible temperature-rise (this temperature-rise being the ultimate limitation of a motor for continuous service) will easily be from 30 to 50 tons more.

An increase in the total weight of a train amounting to from 3% to 10% is perhaps not of itself of so much importance, because such a difference in net power demand can easily appear for various reasons; but a ratio of 2 to 1 in capacity for the limit of equipment possible to install within given allowable dimensions and number of units is a matter of vital importance.

If an increased weight is permissible for any given capacity, there must be some ample compensation for it. Of course this is claimed to be the fact in the single-phase system, but another possible advantage which might prove important is the abolition of gearing and bearings, and simplification in motor and locomotive construction. Both advantages can hardly be hoped for.

Comparative weights of direct-current and 25-cycle single-phase alternating-current motors. While testimony is practically universal that not only is any single-phase motor, whatever the number of alternations, more or less inefficient than a direct-current motor of like weight or capacity, the differences of efficiency, excluding the losses in the gearing, are variously estimated.

A curious illusion relating to this subject seems to possess a number of well-known men, as was illustrated by an active discussion before the English Institution of Electrical Engineers of Mr. F. W. Carter's paper on, "Technical Consideration in Electric Railway Engineering," at the meeting in January, 1906. Mr. Mordey, while stating that there is a large difference in the efficiency of direct-current and single-phase alternating-current motors, claimed that inasmuch as we are concerned with the efficiency of the whole system it makes no difference where this loss appears, and that this difference of energy may easily exist in a direct-current system if the cars are not properly handled. Mr. Carter very properly corrected him, and pointed out that the location of this loss is vital, as it determines the heating of the motors, and if appearing in them it meant from two to three times the heat generated to be dissipated from the equipment. This is but another way of saying that a greatly increased weight of equipment is necessary with the machines of lower efficiency.

The reason for the reduced efficiency of the single-phase motor (whatever the actual amount, which depends upon a number of factors) is inherent, and is due to the transformer action which by increasing the losses limits the output of the motor. There is an additional loss of considerable consequence. Electrical efficiency, it must be borne in mind, is the ratio between the real output and input. The net input is, however, not the product of current and potential, as in a direct-current motor, but is affected by the phase-relation, commonly known as the power-factor; and when this is below 100% it means that the actual watts input is less than the product of potential and current or volt-amperes. To put it another way, the actual current input is greater than would be required if the power-factor were unity. As ordinarily rated, efficiency does not take account of this fact, but the increase of current actually means an increased I^2r loss, hence greater heating, and a consequent further reduction of motor-capacity.

It is well, just here, to point out that an increase of 10% in the amount of current used on a direct-current system, because of improper gear-ratio, change of schedule, or careless handling of equipments by motormen does not mean that this excess energy is dissipated in internal losses in the motors, for these may be increased only about one per cent. The situation in regard to the single-phase motor is, however, entirely different, for it is subject not only to increased power consumption with its proportionate losses because of careless operation, but it also has its individual increased internal loss, which is variously estimated to be much more than that found in properly designed direct-current motors of equal weight and like physical limitations.

Much, indeed, has been stated, and denied on this subject of the relative weights and capacities of direct-current and single-phase alternating-current equipments. On several occasions I have stated that, measured by equal physical limitations in speed and clearances, and for the same temperature-rise with natural ventilation, the total weight for any given service would be twice as much with the alternating-current apparatus as with the direct-current. A similar view has been expressed by other investigators, among whom I may mention Carter, Parshall, and Hobart.

Statements of this character, no matter how authoritatively and carefully made, seem to lie under the suspicion of individual prejudice. Since this is an engineering matter of so much importance, I have endeavored to get some exact facts. These will, I think, prove interesting, and I will show graphically, illustrating somewhat further by specific statements, the actual comparison between two motors of almost exactly the same weight.

It is customary to adopt a single-phase alternating-current motor rating which is based upon the performance of some direct-current motor. For example, a 125-h.p. single-phase machine is supposed to do the same work, that is, handle the total number of tons on some specified service, as a 125-h.p. direct-current motor. This may be an ingenious comparison, but it is a very specious and misleading. The fact is that such a motor equipment, including its transformer, will be very much heavier than the motor equipment with which it is compared, and consequently the net load which it can handle will be much less.

What *is* of vital consequence is a *comparison of capacities for equal weights*, not only of motors but of total apparatus which must be carried on a car, and also to compare the speed-relation and the polar-clearances, in other words, the allowable wear of bearings, all of which is quite aside from gear and commutator brush considerations, which are of themselves serious.

Valatin and others have indicated one measure of comparison between motors of different makes, types, and capacities—the " weight-coefficient,"—which for convenience may be expressed by the following equation:

$$\text{Weight-coefficient} = \frac{\text{Nominal rated horse power}}{\text{Revolutions} \times \text{weight in tons}}$$

This is a factor of the greatest importance, and it should be considered not only for the one-hour 75°-rise load, but throughout the whole thermal curve.

Let us investigate two motors, which for convenience we will call X and Y, both standard modern machines.

An initial comparison is as per this table.

Machine	*Type*	*Voltage*	*Air-gap*	*1-hr. rating*	*Weight*
X	d.c.	550	0.25	240 h.p.	5,473 lb.
Y	25~a.c.	225	0.10	125 h.p.	5,274 lb.

The weights are minus pinions, gear, and gear-cases. There is a difference of less than 4% in net weights, or about 2.5% in total weights. They can, therefore, be very properly compared.

In passing, I would call attention to the air-gaps, that of the direct-current motor being nearly three times that of the alternating-current motor—a difference of vital importance as affecting allowable bearing-wear, and the proper functioning of the armature circuits under practical operating conditions.

The accompanying curves (Fig. 8) show graphically, almost startingly, the comparative speeds, capacities, and weight-coefficients of these machines, all referred to the time required to rise 75° in temperature when operating at full normal potential under varying loads and with natural ventilation.

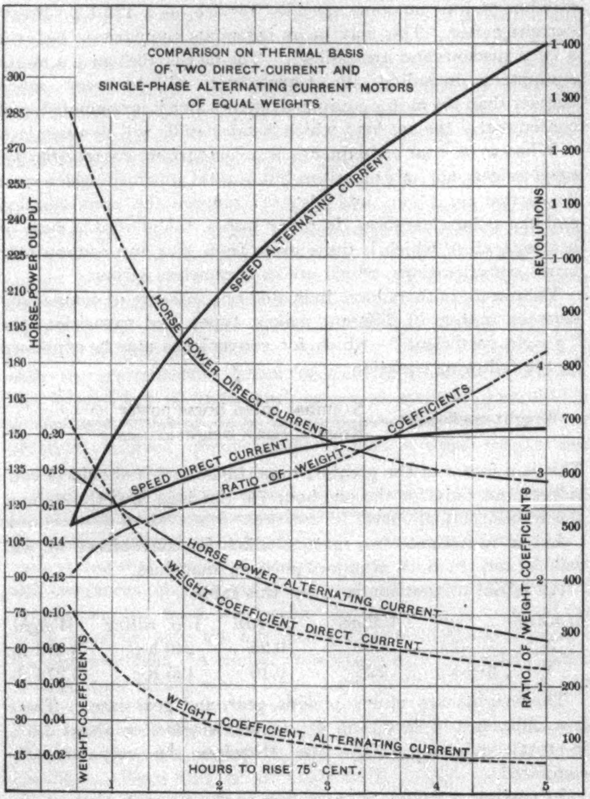


FIG. 8.

It so happens that these two motors have the same speed—

500 revolutions—when run at their proper potentials for 39 minutes with such loads as will give temperature rises of 75°, and hence this will be taken as the starting point, and the characteristics noted for various runs up to five hours.

Inspection of these curves shows the following comparisons:

Time for 75° rise	Capacities		Ratio of capacities	Speeds		Ratio of speeds	Wt. Coefs.		Ratio of Wt. coefs.
	D. C.	A. C.	D.C. ÷ A.C.	D. C.	A. C.	D.C. ÷ A.C.	D.C.	A.C.	D. C. ÷ A. C.
39 min.	285	134	2.13	500	500	1.00	0.208	0.101	2.06
1 hr.	241	122	1.98	530	664	0.80	0.166	0.070	2.37
2 "	172	95	1.81	602	932	0.65	0.104	0.038	2.74
3 "	148	81	1.83	650	1130	0.57	0.083	0 027	3.07
4 "	137	72	1.90	670	1270	0.53	0.075	0.021	3.57
5 "	132	64	2.06	690	1398	0.50	0.070	0.017	4.12

Generally speaking, it will be noted that: starting at 500 revolutions for a 39-minute run, the capacity of the direct-current motor averages approximately nearly double that of the alternating-current throughout the thermal range; the speed of the alternating-current motor rises at a much more rapid rate, until on a five-hour run it is double that of the direct-current motor, despite the fact that it is only developing one half the power; the direct-current motor has a 5-hour capacity in excess of the 1-hour capacity of the alternating-current motor; and the ratio of the weight-coefficients, beginning at a trifle of over 2 to 1, rises to more than 4 to 1 in favor of the direct-current motor on the longer runs. This comparison of weight-coefficients does not include the collectors, control-switches, rheostats, transformers, or wiring, which in the aggregate are enough heavier for the alternating-current motor to maintain these disparities.

It is evident, therefore, that a pair of these alternating-current motors can handle only about one half of the total load of the direct-current motors, with all the disadvantage of higher armature speed and smaller air-gaps; and considering the excess weight of the control apparatus, the net load over and above the electric equipment would be considerably less than one half.

This general comparison is not, so far as the relative characteristics are concerned, individual to this particular size of motor, but seems to be equally applicable through a wide range, and indifferently as to the make, or whether the alternating-current motor is of the series-compensated or the repulsion type. Furthermore, these differences are seemingly so inherent that there is little chance for improvement at 25 cycles.

Let us see the practical application of these facts. The passenger service on a certain typical trunk-line division requires cars of such size that, operated on a direct-current system they would be equipped with 2 X's, and if on a 25-cycle current system with 4 Y's. With equal seating capacity the following are actual comparisons:

a. Total weights of electric equipment, including 500 lb. excess on trucks:

Alternating current,	(4 Y's)	35,000 lb.
Direct current,	(2 X's)	16,000 "
Excess a.c. over d.c.	(118%)	19,000 lb.

b. Total nominal rating of equipments:

Alternating current,	(4 Y's)	500 h.p
Direct current,	(2 X's)	480 "

c. Rating per ton of total weight, including car-body and seated passengers:

Alternating current,	(4 Y's)	9.92 h p
Direct current,	(2 X's)	10.67 "

d. Approximate costs of electric equipment:

Alternating current,	(4 Y's)	———
Direct current,	(2 X's)	———
Excess alternating current over direct current	(100%)	

Polyphase and direct-current motor characteristics. Opposed to the two types of single-phase motors are the polyphase and the direct-current motors, the former with a rotating field and the latter with a field of fixed character. They have similarly high weight-efficiencies, the former having somewhat the advantage when compared with the ordinary type of direct-current motor.

The polyphase motor, however, is a normally constant-speed machine. It can, through a rearrangement of fields, be run at two different speeds; but each is practically a constant one. Or where there is a plurality of motors, half and full speed can be obtained by having one of different character from the other, and operated in cascade relation to it, with the necessity, however, of throwing one-half of the motors out of service when running at full speed. With cascade operation and field changing combined there can be three running speeds. These motors, so far as their supply is concerned, have been limited for practical reasons to a potential of 3000 volts on the trolley, because the supply requires, besides the rail, two wires overhead, although a recent undertaking in the United States, the operation in the Cascade Tunnel, is to be attempted at 6000 volts.

Polyphase motors have an enormous overload capacity, and the fact that they run at synchronous speeds with a very small slip, and if the frequency is unchanged will run upgrade nearly as fast as on a level, would indicate at first sight excessive loads on main and sub-stations. But a curious and perfectly natural result has been pointed out by Cserhati and von Kando, namely, that with suitable provision for regulation at the central station, so that with excessive loads the generators will drop in speed, there will, with such speed reduction, be not only a temporary cessation of drawing power by the locomotive, but there may actually be a return of energy

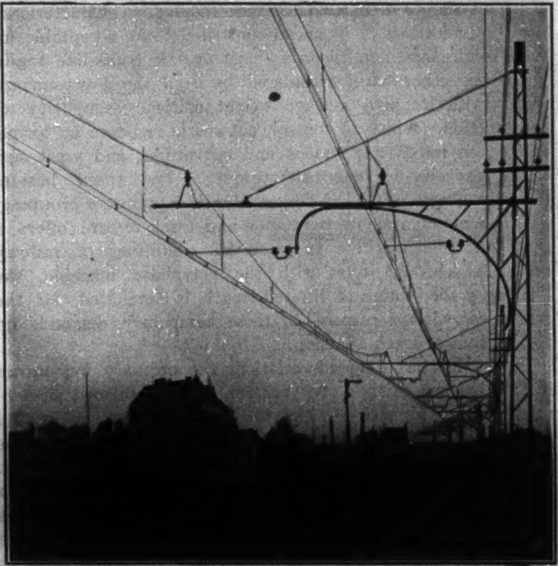


FIG. 9—Multiple catenary on Blankenese-Ohlsdorf Railway

to the line while slowing down. While of course this slowing down affects all trains on a system, it is quite conceivable that when there are a number of trains in operation a mean result may easily be attained which will, in the matter of load-fluctuation, compare favorably with that of any other system. Multiple-unit grouping and operation is ordinarily impracticable because of the small slip. In spite of the splendid work done by the Ganz Company, and the strong support of many Italian engineers, I feel that, all things considered, neither the motor characteristics nor the limitations of overhead construction are acceptable for such service and conditions as exist on our trunk-line roads.

On the other hand, considered by itself, the direct-current motor, with its high average weight efficiency, simplicity of construction, facility of control, automatic response in torque and speed to varying grades and curvatures, and great sustained capacity for enormous torque at low speed, besides the advantages of speed-ranges obtained by motor-grouping, and the use of a single conductor and track return, offers a most effective machine to meet the conditions of railway service. Through it, as with the polyphase machine, the "ruling grade," often of limited length, is eliminated, for the motor can always respond to these temporary demands up to the limit of track adhesion.

In the matter of speed-variation, the ordinary four-motor locomotive has, with proper control, three impressed electromotive forces, for each of which there is the same torque with a given current, while the aggregate current from the line varies as does the speed of the locomotive itself at any fixed torque, about 400 per cent. For each of the combinations there is a wide controlled automatic range of torque and speed, which as the sustained torque increases is far beyond the limits of the single-phase motor, and for a wide range of torque there is possible a considerable variation of speed by field-shunting.

These various features of torque- and speed-control are of the utmost importance when, under some abnormal conditions of traffic, it may become necessary to relieve the demand on the supply, although maintaining a high draw-bar pull, or when, as in the operation of snow-plows a number of pushing locomotives under a single control must run at slow speed for considerable periods of time.

Direct-current motor improvements. During the last two

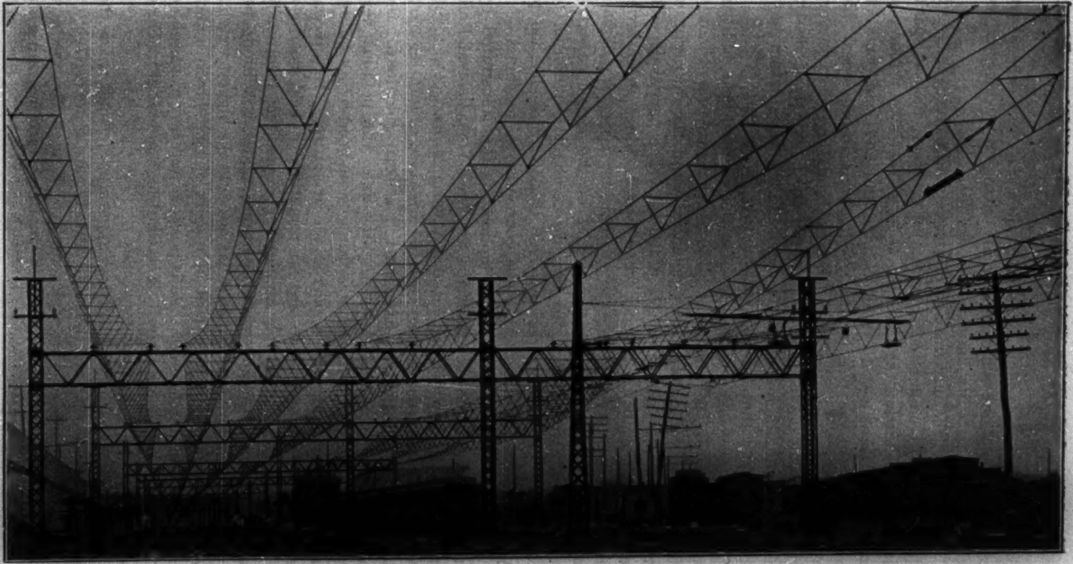


FIG. 10—Double overhead catenary trolley on New Haven Railroad. Four tracks and siding

years important developments have taken place in direct-current motor construction which materially change any preconceived conclusions as to its limitations.

The first is the introduction of the commutating pole, which has practically eliminated commutator troubles, such as sparking, undue heating, and flashing over, so that even a four-pole machine, within a wide range of potential and load, runs absolutely black at the brushes. That this improvement has reached a high degree of commercial standing, despite very recent technical criticism and opposition, is evidenced by the fact that orders for nearly a thousand railway motors have been placed within the last two months.

This improvement makes possible the shunted-field addition to the series-parallel control of speed, the construction of motors for operation at much higher potentials, and the operation of two motors in series at double potential. The partial dependence of one motor on another when two machines are in series is not individual to this combination, for with single-phase alternating-current motors, especially of the larger capacity, the heavy currents required because of the low potential at which the motors are operated—200 to 250 volts—has led to permanent series or series-parallel connection of machines.

An especially important development is that illustrated by the gearless locomotives built for the New York Central Railroad (Fig. 4), in which the hitherto invariable practice of maintaining a fixity of relation between the armature, or rotating part, and the field-magnet, or fixed part, has been abandoned; the armatures are mounted directly on the axle, the field-magnets forming a part of the locomotive-frame, supported by its springs and hence movable with regard to the armatures. In this construction, therefore, there are no armature or field bearings. This locomotive is of the simplest type possible, electrically and mechanically; and when operating under conditions for which it is properly applicable it has not only the highest weight-efficiency, but the lowest cost of repairs of any direct-current machine, and much lower than is possible for any single-phase locomotive. It is structurally a natural high-potential machine on account of having but two poles.

Since the capacity of electrical apparatus depends upon the speed at which, with any magnetic flux, the armature conductors move, this gearless type of locomotive, if used for the slow speed and heavy torque required on freight service, can only

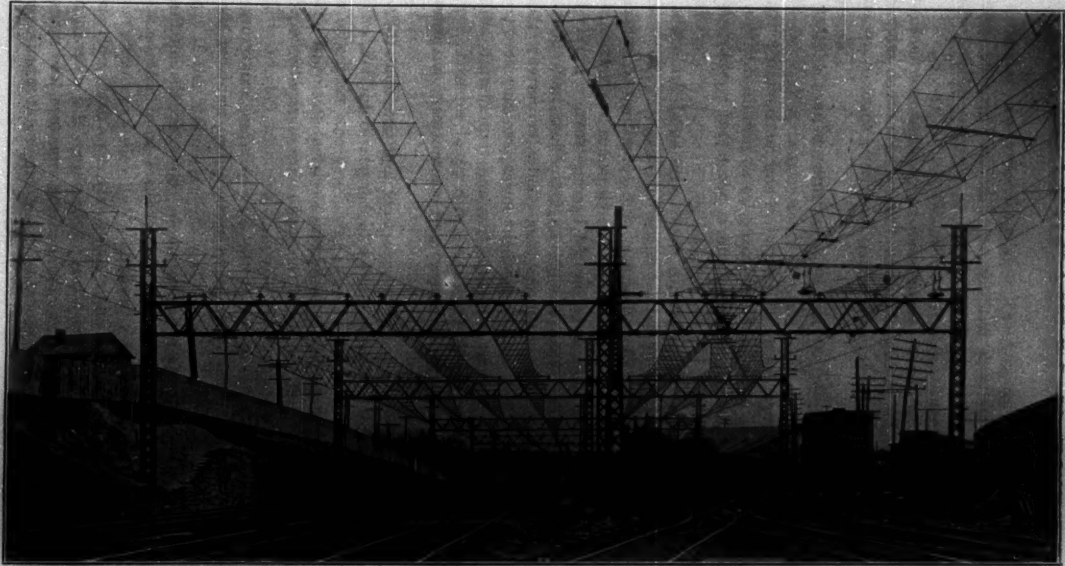


FIG. 11—Double overhead catenary trolley on New Haven Railroad. Four tracks and cross-over

be constructed with reduced weight-efficiency as compared with geared locomotives; but despite this handicap there are so many special advantages that it can be seriously considered even for this service.

Difference between direct-current and single-phase alternating-current motors. The present inherent differences between single-phase and direct-current motors may be briefly summed up as follows:

1. The input of current in one is continuous; in the other intermittent.

2. One has a single frame, the electrical and mechanical parts being integral; the other has a laminated frame contained within an independent casing. Hence there is not equal rigidity, or equal use of metal.

3. One has exposed and hence freely ventilated field-coils; the other has field-coils imbedded in the field-magnets.

4. One has a large polar clearance, and consequently ample bearing-wear; the other has an armature clearance of about only one third as much, and hence limited bearing-wear.

5. One is operated with a high magnetic flux, and consequently high torque for given armature-conductor current; the other has a weak field, and consequent lower armature torque.

6. One has a moderate sized armature and commutator, and runs at a moderate speed; the other, with equal capacity, has a much larger diameter of armature and commutator, and runs at a much higher speed.

7. One permits of a low gear-reduction, and consequently a large gear-pitch; the other requires a higher gear-reduction, and a weaker gear-pitch.

8. The windings of one are subject to electrical strains of one character; in those of the other the strains are of rapidly variable and alternating character.

9. The mean torque of one is the corresponding maximum; the mean torque of the other is only about two thirds of the maximum.

10. The torque of one is of continuous character; that of the other is variable and pulsating, and changes from nothing to the maximum fifty times a second.

11. One has two or four main poles only, two paths only in the armature, and two fixed sets of brushes; the other has four to fourteen poles, as many paths in the armature, leading to unbalancing, and as many movable sets of commutator brushes.

12. One can maintain a high torque for a considerable time while standing still; the other is apt to burn out the coils which are short circuited under the brushes.

13. In one, all armature-coil connections are made directly to the commutator; in the other, on the larger sizes resistances are introduced between the coils and every bar of the commutator, some of which are always in circuit, and the remainder always present.

14. In one the sustained capacity for a given weight is within the reasonable requirements of construction; in the other it is only about half as much.

15. Finally, the gearless type, with armature and field varying relatively to each other, is available for one, but this construction is denied to the other.

Consideration, then, of the characteristics peculiar to each class of motor indicate, not that the single-phase motor cannot be used, but that if adopted the weight or number, and the cost of locomotives or motors required to do the work must be much greater; that the depreciation of that which is in motion will be much higher; and that there will always be an excess weight of fixed amount per unit which must be carried irrespective of the trailing or effective loads. We must, therefore, in many cases be led to the selection of the direct-current motor, that motor which has the higher weight capacity, the greater endurance, and the lower cost per unit of power.

Electric braking. Recuperation of energy to reduce the amount of power used, and to make the motors act as brakes to retard the acceleration of a train, has been a favorite project, and attended by many prophecies since the beginning of the electric railway industry. I confess to having been very early infected with this economic ambition. In fact, I demonstrated mathematically quite correctly and satisfactorily a good many years ago, before the Society of Arts in Boston, that if the Manhattan Elevated Railway of New York could be equipped electrically with shunt-wound motors whose speed-variation was effected partly by resistance in the armature circuit and then by variation of field strength, there would be a reduction of central-station capacity of fully 40% as compared with a system which did not use the motors as braking generators; and not only was there this theoretical reduction in capacity, but since every stopping train, and every train on a

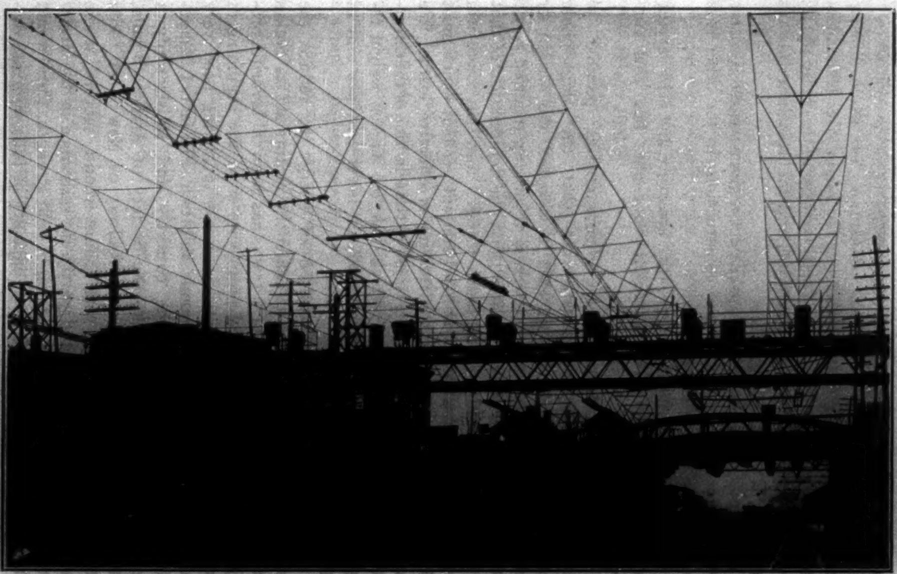


FIG. 12—Double overhead catenary trolley on New Haven Railroad
Cross-over, anchor bridge, and section switches

down-grade was a moving generator there would naturally be materially less losses on the line. These facts were demonstrated practically by experiments carried out on the Thirty-fourth Street branch of the elevated railroad for several months in the winter of 1885–6. But the system is not used to-day, despite its enormous possible saving of power and station capacity,

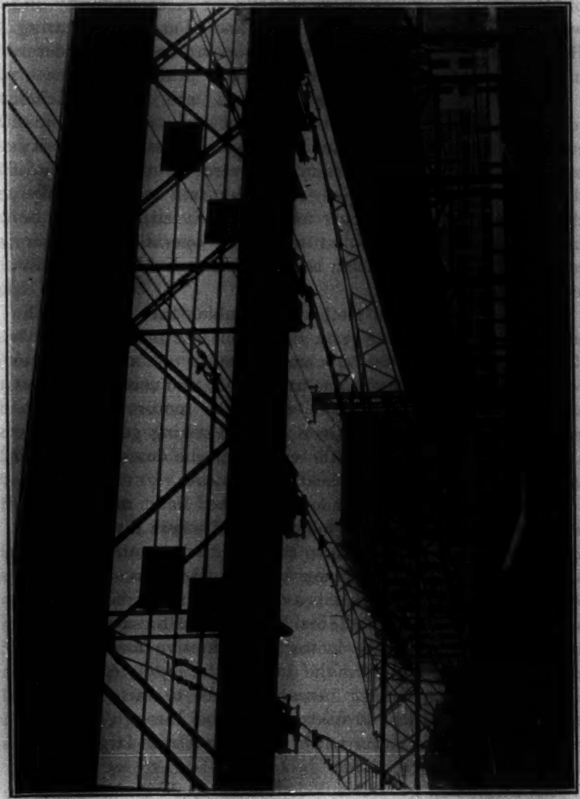


FIG. 13—Double overhead catenary trolley on New Haven Railroad. Depression under crossing highway bridges

because it required the use of shunt motors with their fine-wire field-windings, and hence necessary reduced capacity compared with the modern series motor; it required, also, a very exact equalization of the characteristic of motors and maintenance of like wheel-diameters, and an increase of motor-capacity and weight because of the double duty and consequent heating. Here again capacity has been an important and finally determining factor in motor requirements and practice.

On ordinary railroads the gradients are not sufficient to make it worth while to attempt any recuperation of energy; the acceleration due to any excess of gravity-coefficient above that necessary to overcome the friction of the train is usually welcomed. On mountain roads, however, electric braking may become an important adjunct, not because of power economy, but for safer operation. In any case, simplicity of application and absolute reliability of action are first essentials.

There are two general methods available: one, in which the energy of the descending train drives the motors, acting with shunt- or independent-field characteristics, at an aggregate potential above that of the line at the rail, and sending current back into the line; another in which the motors are disconnected from the line, and driven as self-exciting generators on a closed circuit, as much of the energy of the descending train as desired being used up in heating rheostats.

The first method is dependent on the line, requires external excitation of the field-magnets, and where direct-current motors are directly connected to the line, two armatures should be thrown in series if the power to slow the train down to or below its ascending speed on heavy grades is desired. This is because the excitation of the fields is carried to saturation on ascending work, when the motor electromotive force is much less than that of the line plus the drop on the supply conductors, and permits of no further increase of flux to raise it. Such independent excitation of fields should be through a motor-generator set to get the current of low potential in large volume necessary for the series fields.

This method is, of course, possible of application, and will give a range of control of speed from about the mean speed on ascending grades to double that speed; but it will be with inequality in heating of the armatures and the fields, the latter running cool, and the former practically at their average maximum.

It is not practical to set the control for a given down speed, and then to vary speed by the air-brake, for the braking power of the motors is measured by the relation of their potential to that of the line, which is variable. To be effective, this potential must be raised sufficiently above that of the line, wherever a locomotive may be, not only to send back current, but current in considerable volume over the conductors intervening between it and such other locomotives or stations as may be able to take up the energy thus created. The motors are therefore under a constantly varying condition, and are also subject to excess potential strains. Application of the air-brake to slow down a train would under such circumstances reduce or destroy the braking power of the motors unless their controllers were simultaneously moved. In fact, such air-brake application could readily convert the machines into motors taking current from the line, and hence put double duty on the brake-shoes.

The second method of braking is to use the motors without disconnecting the field and armature circuits from each other, simply closing them upon themselves, and varying the resistance in circuit, the reversers on down grade being set for backward movement. This method requires no change in the organization of the machine, puts equal duty on armatures and fields, as in ascending grades, and the duty on the armatures being considerably less than in the other method of braking they will heat much less.

This method, if provision be made for moving the controller, is independent of the line, and permits of the most complete variation of speed, from the highest permitted to the lowest at which it may be desired to operate, without any use whatever of the air-brake, unless desired, and without in any manner interfering with the application of the latter, although, of course, to get the best effect, both motor-controller and air-brake should be used with regard to each other. There is, however, no possibility of the application of the latter entirely destroying the braking power of the motors.

This latter method of braking does not depend upon line supply, nor require the interposition of any motor-generators, and is therefore more direct and reliable. Another fact of importance is that the aggregate motor potential strains are less. Provision for both methods of braking, although possible, is not advisable because of the introduction of too great a variety of apparatus and methods, which may give rise to confusion and accident, and which in all cases of railroad operation should be avoided as far as possible.

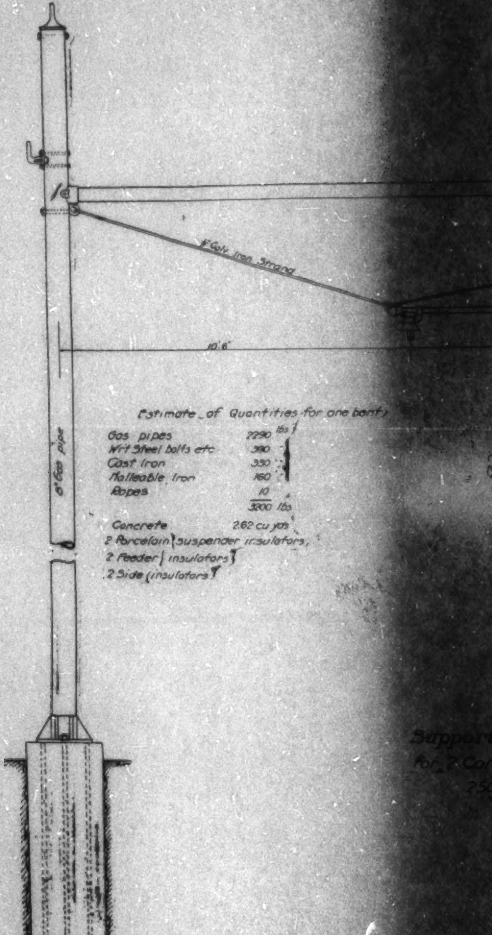
With polyphase motors kept in connection with the line, the braking effect is very similar to that of pure shunt motors, and the excess of down speed is very small. It is doubtful, however, whether with the varying grades and curves of our mountain roads it is desirable to run down-grade at an approximately fixed speed, but rather it seems likely that the existing practice of speeding where the grades and curves are light, and reducing the speed where the grades are heavy and the curves are sharp will remain the preferred practice.

Self-exciting braking is impracticable with polyphase motors.

Comparison of direct-current and alternating-current braking. On the general subject of braking it should be pointed out that with direct- or continuous-current motors there is always a residual magnetism in the fields because of their construction, and the fact that the exciting current never changes direction. Such machines, therefore, can always promptly build up automatically when properly closed upon themselves and the reverser is set in the proper direction.

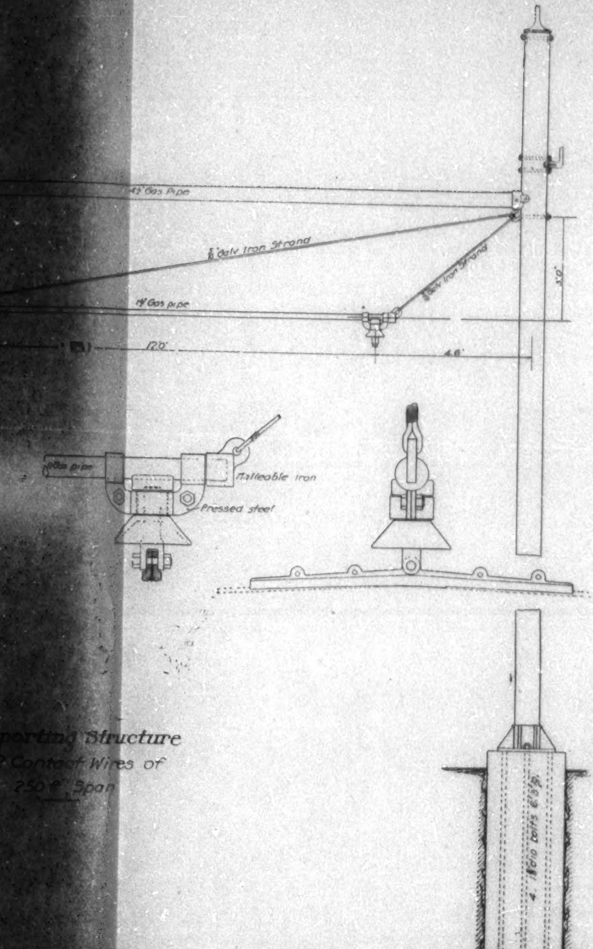
A similarly effective method of braking has been claimed for motors operated by single-phase alternating currents, but it would seem that in this case there is not the same degree of reliability. In such motors the field is laminated to the last degree to cut down heat-losses and to increase the capacity; it will hold but little residual magnetism under any circumstances, and furthermore the field is excited by a rapidly varying alternating current. It is therefore possible that at times the field will be nearly inert, and comparatively slow, with its low-turn winding, in building up, or possibly the field may be entirely inert, and refuse to build up at all. There seems, therefore, no certainty whatever that a single-phase alternating-current motor, disconnected from the line, and without any other exciting source, will, when closed upon itself, always build up into a braking dynamo.

Aside from the ordinary objection of having such a possible failure, the consequence might be serious should it be necessary suddenly to call upon the machines to brake; as, for example, when getting underway, or when slowly ascending a grade there should be a failure of current, and the train begin to back down before the air-brakes were applied, or in case for any reason they should not be promptly available.



3/8" Galv. Iron Strand
10'6"
8" Gas pipe
Estimate of Quantities for one bent;
Gas pipes 2290 lbs
Wrt Steel bolts etc 390
Cast Iron 350
Malleable Iron 160
Ropes 10
3200 lbs
Concrete 2.62 cu yds
2 Porcelain suspender insulators,
2 Feeder insulators
2 Side insulators
Support
for 2 Co
250

FIG. 14.—Joseph Meyer's


1½" Gas Pipe
⅝" Galv Iron Strand
⅝" Galv Iron Strand
1¼" Gas pipe
3'0"
12'0"
4'0"
Gas pipe
Malleable iron
Pressed steel
4. 1⅛ dia bolts 6'3" lg.
porting Structure
Contact Wires of
250 ft Span

er's method of suspending trolley wir

(Mayer)

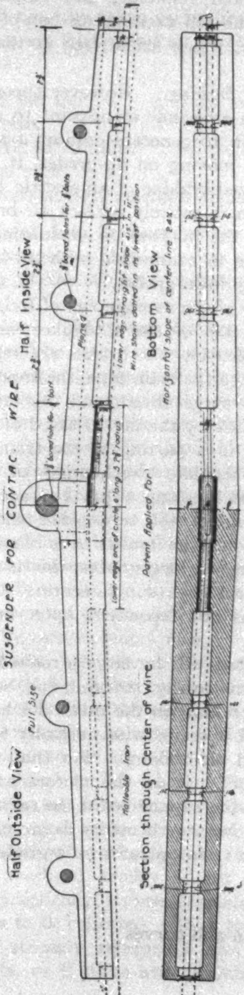

SUSPENDER FOR CONTAC. WIRE
Half Outside View
Full Size
Malleable Iron
Half Inside View
Planed
bolt
Lower edge arc of circle 6' long 5 ft radius
Lower edge straight slope 4.5" in 11"
Wire shown dotted in its lowest position
Patent Applied For
Bottom View
Horizontal slope of center line 2.4%
Section through Center of Wire

FIG. 15.

All things considered, reliability and simplicity of operation dictate the use of the self-exciting method of braking with the direct-current motor, which lends itself to that purpose in the highest degree.

Extent of electric braking. However theoretically desirable it would be from an economic standpoint to utilize the energy of a descending train to generate current available for partial propulsion of trains moving on up-grades, it is to be borne in mind that the localized braking of an electric locomotive is not intended to, nor can it entirely replace air-braking; it is proposed primarily for the purpose of eliminating certain existing troubles unavoidable in connection with air-brakes when used continuously on long down-grades.

In trains made up of the average run of freight cars there is a non-simultaneous action of the air-brakes, and often, if after long continued application the brakes are released for a brief time so as to re-charge the train-pipe, the front end of the train being unbraked will surge ahead, and the rear part will for a brief time be held back by the non-released or partially released air-brakes, resulting in a parting of the trains.

Another serious trouble, overheating of brake-shoes and wheel-rims, leading to breakage of parts on account of expansion or sudden chilling, cannot well be avoided where there is such a continuous application of air-brakes as is required on free movement of freight trains on long grades; this is a difficulty which it is best to avoid by supplementing the air-brake by other braking means not dependent upon brake-shoe application.

The objections cited will be largely removed if the duty on air-brakes can be materially reduced, and sometimes entirely relieved. Electric braking on the method I have indicated will accomplish this, and it seems wise normally to divide the duty between electric and air-braking. For that reason I will give an illustration of the duty on the motors, as this will have a direct bearing upon the capability for the radiation of energy in the form of heat from the rheostats in circuit.

Suppose a 700-ton train operates on a grade requiring tractive efforts per ton of,

For lifting	25 lb.
For traction and curves	8 "
Total	33 "

On down movement, 17 lb. only will be available for acceleration of speed, which must be taken up by braking in some form.

If divided between electricity and air there would be required from the locomotive:

Average retardation per ton	8.5	lb.
Total for 700-ton train	5950	"
Foot-tons per minute, at 20 miles	5192	
Equivalent electrical rate	235	kw.
Dissipated in rheostats at 90% machine efficiency	212	kw.

which would be a light duty for four motors and rheostats, and would leave ample margin for them to take the full braking effort up to the skidding of the wheels whenever it might become necessary.

Working conductors. Whatever motors are used—and all the principal types will be used—there is a variety of methods of construction and use, especially as applied to locomotive building, and alternate methods of current supply and use.

Generally speaking, conductors may be divided into two classes; flexible or rigid overhead, and third-rail. One would suppose from many references and some of the arguments which have been made, that direct-current systems are essentially and necessarily dependent upon the third-rail, and that the overhead trolley is a thing individual to, and has been developed for alternating-current operation only. This impression should be corrected, not of course for the information of engineers, but because this somewhat erroneous idea is in danger of being accepted as a fact by non-technical men.

The overhead system has been a distinctive feature of all electric roads operated by direct current since the days of the historic Richmond road, with the exception of those using the third-rail; and until recently the only practical modification has been the somewhat limited use abroad of the sliding bow or roller in place of the grooved trolley-wheel. This latter, although used with high speeds on interurban roads, is unfitted for trunk-line operation, and where overhead trolley wires are used the long collector will probably take its place.

Physically, the overhead trolley is not individual to any particular system; practically, its use depends upon the amount of current which has to be collected. If at low potentials, then it must be either strongly reinforced, and there must be a plurality of contacts, or if these are diminished the amount of current to be collected must likewise be reduced and the potential raised. In the abstract, therefore, the possible use of the overhead trolley, no matter by what system, is a question of allowable operative potential, and the amount of current which can be practically collected.

Identified as I have been with the development of the overhead trolley, I cannot but feel a pride in what has been accomplished with it, nor shut my eyes to a certain fascination in the conception and knowledge that there may be transmitted over great distances, and taken at will from almost a spider's web, an enormous power. An ardent advocate for years of the use of higher potentials, and fully aware of the limitations of the direct-current standard which has existed so long, I believed for a long time in, and advocated the use of the overhead trolley as the only practical working conductor for potentials above 1000 volts.

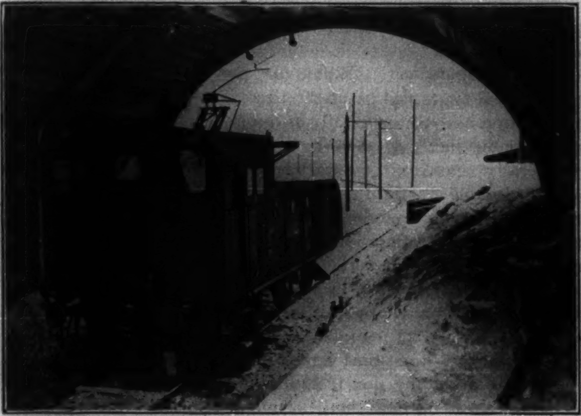


FIG. 16—Oerlikon trolley in tunnel—single-phase M. G. Locomotive

Until recently, the invariable practice with overhead construction has been to use a flexible wire supported at comparatively long distances on tangents, with pull-offs at curves, and easily yielding to the pressure of a trailing trolley. This is the practice which characterizes not only direct-current trolley operation, but has also distinguished practically all operation abroad where single-phase or polyphase currents have been used. The introduction of high tensions has, however, now made it necessary to provide by additional supports against the possible breakage of the trolley-wire. This had led to the introduction of catenary construction, the catenary being either single, and supporting the trolley at frequent intervals, or double to prevent lateral swaying. In the former case, the

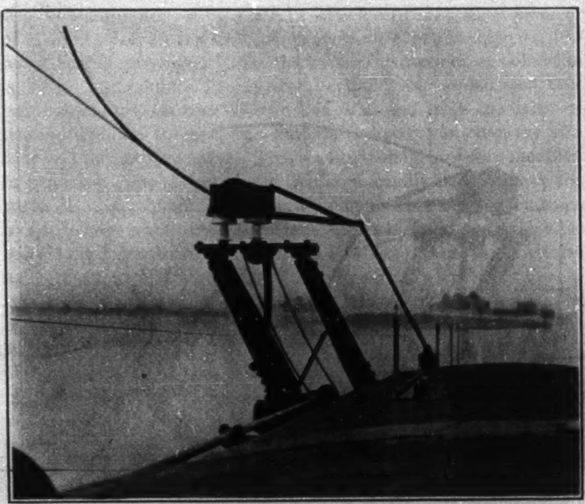


FIG. 17—Oerlikon trolley—over-contact

trolley is only partly flexible, and in some cases the support has been supplemented by an intermediate catenary, as on the Blankenese-Ohlsdorf railway (Fig. 9), where greater flexibility of the trolley-wire itself is insured by loosely suspending it from the lower member of the catenary instead of making the latter the trolley-wire, and providing for varying the tension. In other cases it is to some extent maintained by having less frequent supports, and also by introducing a movable part at the suspender.

The most recent and extended application of double-catenary construction is that on the New Haven road for use with its single-phase locomotives (Figs. 10-13). Here a trolley wire is put under high tension, and is supported at frequent intervals by solid clips attached to rigid triangles, in turn secured to galvanized iron wire cables carried on insulators on the top of bridges which span the tracks at intervals on tangents of about 300 feet. The catenaries are drawn together between the spans so as to give the utmost rigidity to the whole system, the intent being to maintain the trolley-wire as nearly as possible in one plane. At cross-overs and sidings (Fig. 11) the supporting triangles overlap, and the angle between the junction and the trolley wires is filled with additional conductors, more readily to insure safe passage of the vertically moving sliding contact which has been adopted. At intervals of about two miles the trolleys are sectionalized at anchor-bridges, (Fig. 12) where are provided the

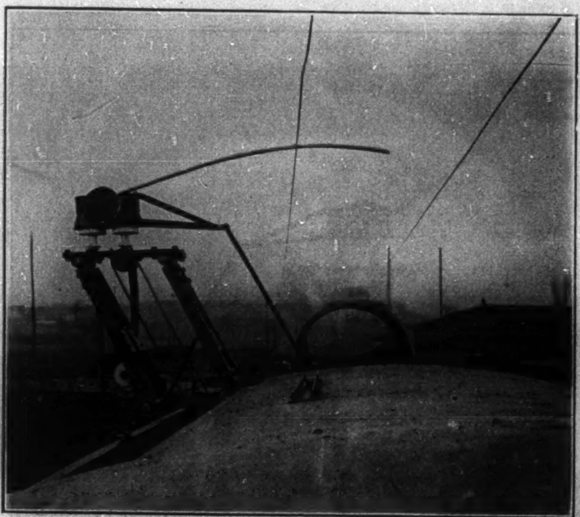


FIG. 18—Oerlikon trolley—under-contact

necessary switches for cutting out sections, and for looping to extra supply conductors.

Among the innumerable trolleys which were tried in early days was a roller of considerable length, mounted at the end of a rod having a vertical telescopic motion in a tube carried on top of the car, and pressed against the wire by a spring in the tube. This was abandoned in favor of the trailing trolley which would more readily follow variations in the trolley-wire. The modern pantograph is an elaboration of this early idea, and has a very much greater latitude of vertical movement. It consists of a sliding or rolling contact, which forms the upper member of a light, yet strong collapsible structure maintaining an upward spring pressure. The theory of this system of collection is, of course, that a locomotive normally moves between two parallel planes, on one of which it runs and from the other of which it collects current, and that the ordinary motion of the contact will be inappreciable. This assumption is, however, modified in practice. The collectors are carried normally 22 feet above the track on a superstructure (Fig. 7) which must respond in some measure to track irregularities, and which has considerable inertia and some friction. There is a drag because of friction against the trolley-wires, and wind-pressure due to motion of the locomotive. This upward pressure must necessarily be changeable because of variation of angle, friction, and the resultant motion; to maintain contact it must rise and fall. When travelling 70 miles an hour it passes supports which are more or less rigid nine times a second, and between these supports the trolley-wire, no matter what the tension, will be convexed upwards. As the collector approaches any suspender the pressure will normally considerably increase, and, as it leaves, will diminish. The practical question arises, whether, considering all the forces acting on it and its inertia, it can satisfactorily respond, in addition to other requirements, to a double change in vertical direction nine times a second. If contact depended upon the whole structure of the pantograph moving thus rapidly some trouble might be anticipated, but possibly the elasticity of the upper part will prove sufficient.

It is interesting to note that Mr. Joseph Mayer, the former chief engineer of the Union Bridge Company, in a paper read before the American Society of Civil Engineers, and also in several other communications, has given a great deal of thought to the question of overhead construction, and has made elaborate calculations of strains involved. His conclusion was to the effect that no trolley wire put up under high tension, and supported in the rigid manner provided by the present catenary, offered either a sufficiently safe or economical method of construction, and he was therefore led to the development of two departures in practice. The first was the use of an overhead rigid iron rod 1.25 in. in diameter, suspended by catenaries, and provided with extension-joints; the second (the first method apparently having been found too expensive) is a method of flexibly supporting a trolley-wire at long intervals from inverted pivoted suspenders which provide a support for the various section-lengths according to the end-slopes (Figs. 14, 15). The suspender grips the trolley only along the center, and then it opens out in large radii to give a graduated resistance to both vertical and lateral deflection. Mr. Mayer's analysis of conditions, the mathematical deductions, and his proposed remedies as illustrated by his detail plans well merit serious consideration.

An ingenious method of making contact with an overhead single trolley-line is that developed by the Oerlikon company under the direction of Mr. Huber (Figs. 16, 17, 18). In this system the trolley is stretched with comparative rigidity on top of insulators supported on posts alongside the track, with cross-overs where needed. In place of the ordinary wheel and bow trolleys, a curved hinged arm of fair length, and sweeping over nearly one half a circle in a plane transverse to the line of track, is supported on insulators on the side of the car. Normally, this bow rests on top of the wire, pressing lightly on it, and thus avoiding the under formation of icicles. On cross-overs and in tunnels, where the trolley-wire is carried over the track, the arm swings toward the center of the car, and is depressed, making contact progressively from the top around to the side and then underneath the trolley-wire. In addition, the saddle which carries the bow is movable laterally, increasing the radius of action. Of course two bows can be used. I believe that in some of the experiments a roller has been tried. Two difficulties present themselves; one the fact that the wire is pressed down from the top, the strain of the weight being added to by the pressure of the contact bar, which can be, and I believe has been on one test minimized by having the wire supported by and above two catenaries, just the reverse of the New Haven practice; the other objection is that at cross-overs the trolley-wire is very close to the top of the car.

The system is somewhat similar to one originally proposed in my earlier trolley work, where two vertical rollers with universal flexible support made contact, one on each side of a trolley-wire, and at crossings one was deflected below it. This was not put into practice.

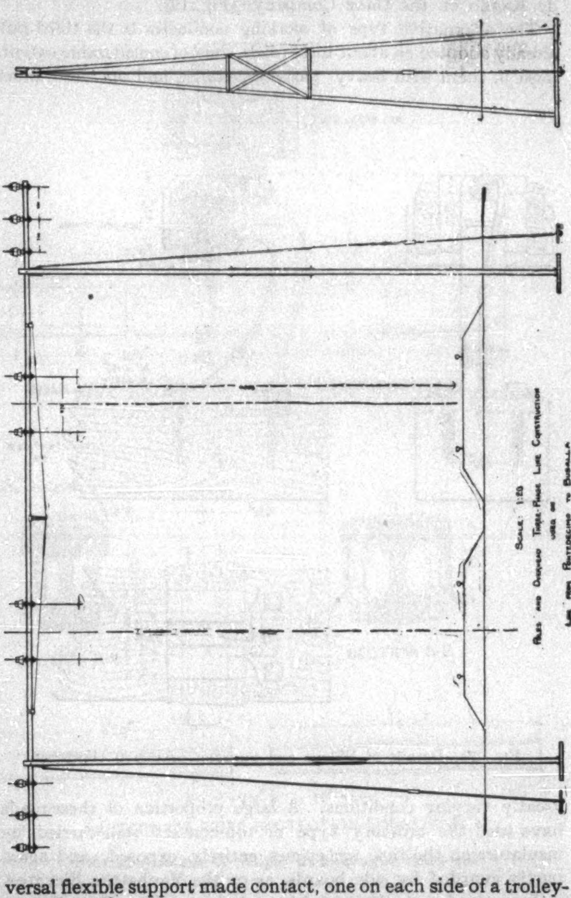

Scale: 1:20
Poles and Overhead Three-Phase Line Construction
used on
Line from Pontedecimo to Busalla

FIG. 19—Ganz overhead trolley support

A very neat structure for the overhead trolley, whether of the ordinary or catenary suspension, is that designed by Mr. C. de Kando of the Ganz Company, (Fig. 19).

The alternative type of working conductor is the third-rail. already adopted on about forty roads, some of considerable extent, most of them with heavy passenger traffic, and operated under greatly varying conditions. A large proportion of these roads have used the ordinary type of top-contact rail, carried by insulators on the ties, sometimes entirely exposed, and again partly guarded by side boards, as on the Manhattan Elevated, or by a wooden shield carried by yokes from the rail itself, as on the Interborough. While this is the simplest form of third-rail

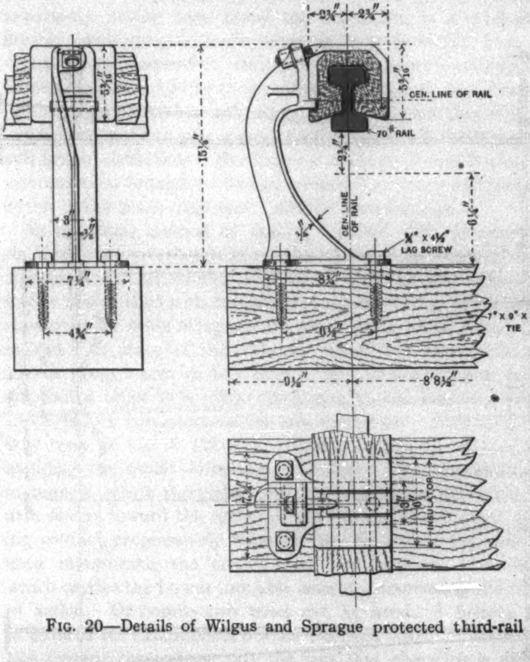
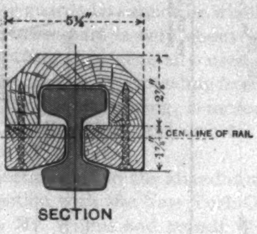
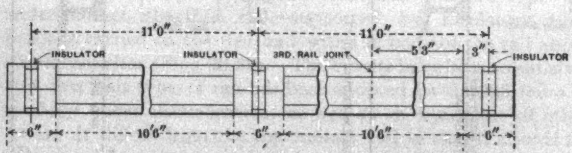

2¾"
2¾"
5 3/16"
CEN. LINE OF RAIL
70# RAIL
5 3/16"
15⅛"
2¾"
CEN. LINE OF RAIL
6⅛"
¾"
¾" x 4½" LAG SCREW
3"
⅜"
7¼"
4¾"
8¼"
6¼"
7" x 9" x 9'6" TIE
9⅛"
8'8½"
7½"
3"
6"
INSULATOR

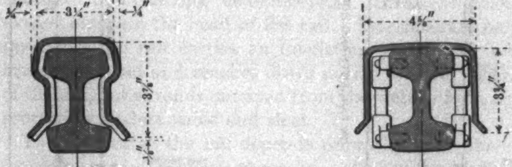
FIG. 20—Details of Wilgus and Sprague protected third-rail


5⅛"
2⅜"
CEN. LINE OF RAIL
1⅞"

SECTION

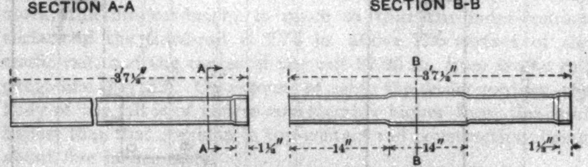

11'0"
11'0"
INSULATOR
INSULATOR
3RD. RAIL JOINT
5'3"
3"
INSULATOR
6"
10'6"
6"
10'6"
6"

INSULATOR AND WOODEN PROTECTION SHEATHING


¼"
3¼"
¼"
3⅞"
⅛"
4⅝"
3⅛"

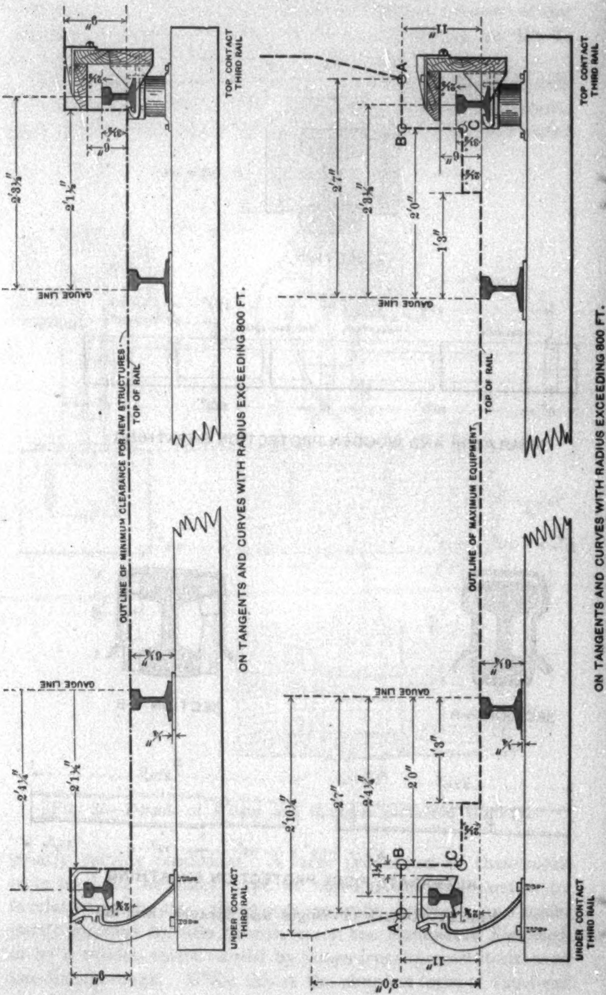
SECTION A-A

SECTION B-B


3'7½"
A
A
1⅛"
B
B
3'7½"
14"
14"
1⅛"

ALTERNATE FIBRE PROTECTION SHEATHING

Fig. 21—Details of Wilgus and Sprague third-rail


TOP CONTACT THIRD RAIL
UNDER CONTACT THIRD RAIL
GAUGE LINE
OUTLINE OF MINIMUM CLEARANCE FOR NEW STRUCTURES
TOP OF RAIL
OUTLINE OF MAXIMUM EQUIPMENT
9"
3½"
6¾"
¾"
2'3½"
2'1½"
2'4½"
11"
2'7"
2'3½"
2'0"
1'3"
2'10½"
2'4½"
1¼"
2'0"
A
B
C

ON TANGENTS AND CURVES WITH RADIUS EXCEEDING 800 FT.

ON TANGENTS AND CURVES WITH RADIUS EXCEEDING 800 FT.

FIG. 22—Clearance diagrams—equipment and third-rails

construction, and has given good service for years, it has certain disadvantages. If exposed, it is a constant menace, especially in yards; and even when guarded it cannot be wholly protected from snow and ice. The lower part is only about four inches above the tie, while the holding-clips generally used reduce even this clearance, so that the danger of grounding from accumulation of wet snow and ashes, and from flooding, is increased. In the latter case, over-all flooding has the whole rail-surface for leakage.

These various objections led to the abandonment of the top-contact rail in connection with the New York Central work, and the development by Mr. Wilgus and myself of a new type—an under-contact sheathed rail—supported by insulators from brackets carried on the ties, and with the body of the rail about nine inches clear (Figs. 20-29). The results have been so satisfactory that this type of rail has been adopted for the 285 miles of trackage under electrification, as well as on a number of other roads. It differs from the top-contact rail in that it affords far greater safety, more certainty of continuous operation, and can be used with higher potentials.

The structure consists, briefly, of a series of iron brackets carried on the ties, to the tongued vertical face of which are clamped non-charring moisture-proof insulator-blocks which loosley embrace the head of the rail. Intermediate between the insulators the rail carries an insulating sheathing, which embraces the head and reaches down nearly to the bottom face of the rail, but extends outward from the web to form a petticoat protection against snow and sleet.

The position of the rail depends primarily upon the clearance requirements. To meet those of ordinary trunk-line rolling stock, the bracket-height is made so that the under-contact surface of the third-rail is 2.75 in. above the surface of the traffic rail, and the center of the rail 27.25 in. from traffic rail gauge line (Fig. 22). On account of using the under-contact, the body of the rail is of course considerably higher from ties and ballast than that common in top-contact rail construction, being about five inches more.

On crossings, the horizontally extending flipper-shoe, pressed upwards by a spring, lifts and clears the traffic rail by a fairly safe margin. At switches, to accommodate the lateral displacement of a locomotive when taking the siding, while not reducing the clearance from the protective sheathing on the straight track, the lower head of the rail is specially formed; a similar construction is useful for engaging the shoe when entering a straight track from an angle.

For moderate potentials, say of 600 volts, the two halves of the insulator-blocks are alike, but for the higher potentials the inner insulator-block, that is, the one next to the face of the bracket, is extended so as partly to shroud the head of the bracket. The sheathing between the insulator blocks, depending upon local conditions and price of materials, as well as potential used, is formed of three wooden strips, one grooved on the under side and enclosing the head of the rail, and the other two, attached to and dependent from it, reaching in towards the web of the rail. Where good wood is not available, an alternate protection, costing about the same and having a higher electrical resistance, although not quite so good a mechanical one, is a semi-flexible shell of indurated fibre conformed to the rail-section.

Fig. 23—Three states of third-rail construction, New York Central

To get the highest protection both mechanically and electrically, the two methods of sheathing can be used, or in place of the inner sheathing of indurated fibre the wood sheathing can be carried slightly removed from the rail-surface by non-hygroscopic saddles; this leaves an air-space between the wood and rail, prevents warping, and affords the necessary physical support for rigidity.

At passenger stations, where special precaution may be deemed advisable, and in freight yards, the double protection can be used, and any required thickness of insulation adopted without reducing clearances by reducing the cross-section of the rail at these points. The conductivity will of course be made up by the number of rail-circuits in parallel at these points.

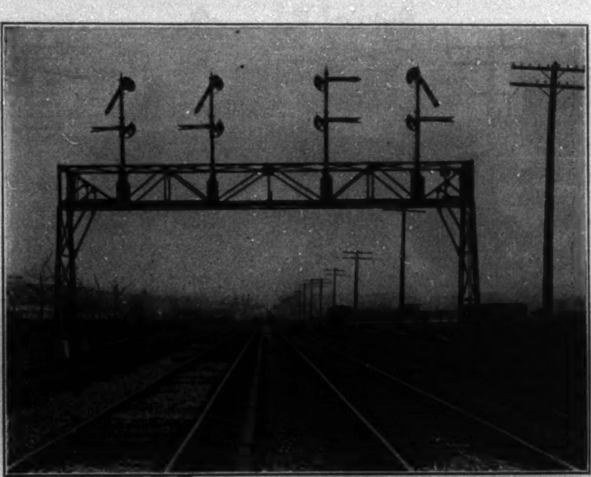


FIG. 24—Protected third-rail on 4-track division, New York Central

This protection is of such character that passengers, as well as employees in the normal discharge of their duties are well protected. In sleet-storms none reaches the contact surface, small icicles only forming at the edge of the petticoats, and these are easily broken off by the passing shoe.

Of course there is no packing of snow between protection and contact rail, and the increased distance from the ground reduces the tendency to leakage. An accidental advantage is a reduction of the tendency to creep and buckle because of less abrupt and wide changes in temperature.

General comparison of working conductors. All working conductors are in many ways objectionable, but since they are a necessary connecting link between the source of supply and the motors, some comparisons may be made of the two kinds, the under-contact, protected type of third-rail and the overhead trolley, as affected by construction and operation.

The third-rail is an inert structure, it can be aligned accurately with the track, is not under strain, and its expansion can be readily taken care of. The overhead trolley is necessarily a system under strain, and where permanency is desired and high potentials are used it must be carried by one or more catenary cables, which on roads of high curvature makes the construction more difficult. Its alignment in the latter case does not correspond with the line of track, and as ordinarily constructed it is subject to extreme variations of tension on account of weather changes.

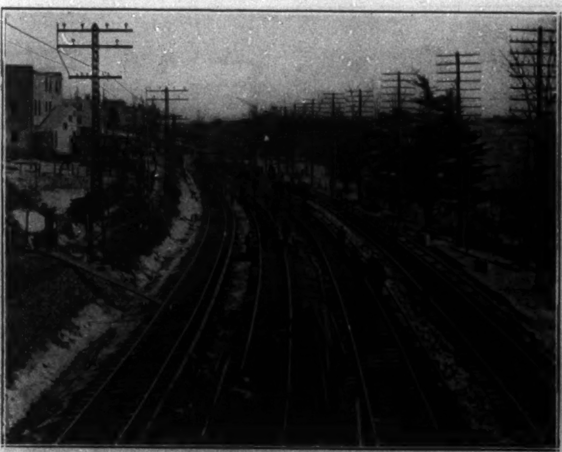


FIG. 25—Third-rail reconstruction after wreck

The third-rail offers some hindrance to the ordinary maintenance of track; but overhead construction is inelastic, and the laying of additional tracks, or changes in grades or alignment require radical and expensive alterations or additions in permanent overhead structures.

Derailments will crush one form of conductor to the ground, forming a short-circuit which will cut off the section; but they may also knock down the supporting structures of the other, and, where there is a plurality of tracks, put them all out of service.

In wrecking, the third-rail offers some obstruction to the throwing of the equipment to one side; but on the other hand, overhead conductors may interfere with the operation of the crane-booms of the wrecking car.

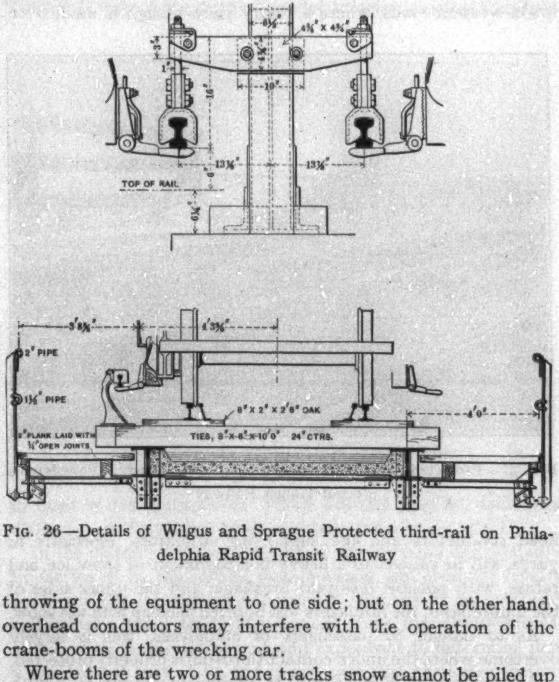

6½"
4⅜" x 4⅜"
3¾"
4⅝"
1"
10"
16"
13⅜"
13⅜"
TOP OF RAIL
6"
6¼"
3'8⅞"
4'3⅜"
2" PIPE
1½" PIPE
8" x 2" x 2'8" OAK
4'0"
2" PLANK LAID WITH ½" OPEN JOINTS
TIES, 8"x8"x10'0" 24" CTRS.

FIG. 26—Details of Wilgus and Sprague Protected third-rail on Philadelphia Rapid Transit Railway

Where there are two or more tracks snow cannot be piled up between them if the third-rails are located there; but on the other hand, overhead conductors are a source of danger to train men, to snow-shed and tunnel repairers, and in the open are subject to troubles of sleet formation.

The third-rail will oftentimes be covered with snow, but is unaffected by sleet. Very thorough tests made in connection with the New York Central work show satisfactory operation, not only in sleet-storms but with the rail buried in snow. Additional depth should not add much difficulty. With regard to frogs and switches, there are no problems which cannot be solved with this type of third-rail, with an occasional overhead section, and any required amount of power can be collected at operative speeds.

On western roads, where a rotary snow-plough is used, overhead conductors and the supporting insulators, especially in yards, will be subject to a heavy bombardment of snow, ice, and refuse, with possible resultant breakage, and the under sides of the umbrellas of the insulators will be often filled up with wet snow.

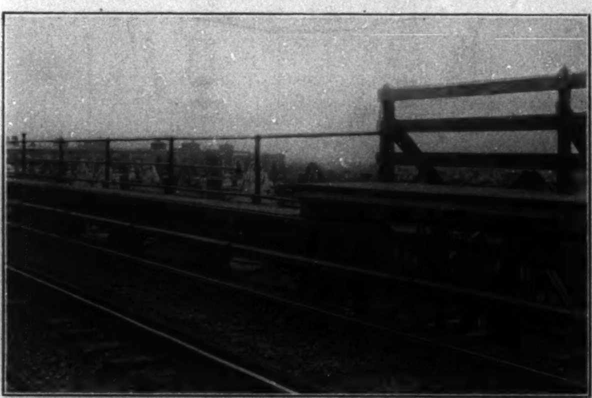


FIG. 27—Protected third-rail suspended from above. Philadelphia Rapid Transit Railway

As to danger to passengers or employees, this is largely overcome where the under-contact third-rail is properly protected, and is designed with due regard to equipment clearances. With an overhead high-tension trolley, there is, on trunk railways, where there are overhead street or highway bridges, tunnels, and snow-sheds, great possibilities of danger because of rearing equipment in case of derailments or collision, and the physical necessity of often bringing the trolley within a short distance of the cars.

Then there are corrosion and soot deposits when steam and electric operation are maintained over the same track. Where the steel supporting bridges also carry signals, as is proposed in some cases, there is increased danger to men engaged in cleaning, painting, or repairing overhead structures, and taking care of signals; and when spanning two or more tracks there is a possible interception of the train operator's view of signals because of dips in the railroad grades bringing overhead bridges in front of the semaphores, which likewise may be made less distinctive if they have truss members for a background.

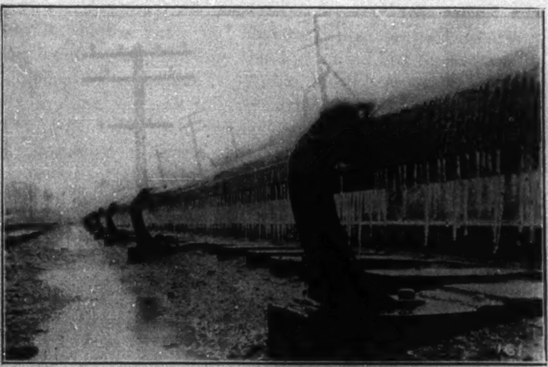


FIG. 28—Protected third-rail after sleet storm

In the matter of inspection, that of the third-rail can probably be carried on by the regular section hands, and ordinary repairs made without interfering with traffic. Repairs of an overhead system on a main trunk-line present some special difficulties. It will often require judgment and experience to determine just where trouble may exist, and in any case that particular section of the line must be absolutely cut out and made dead. If the repairs be other than at a rigid cross-suspension, it would seem that they would have to be made from the top of a structure. running on, and for the time being occupying the rails, and propelled by its own power. The old practice common to street overhead trolleys is of course unavailable; there a construction wagon can drive on to the track and off again at will, and the line even while alive can be readily repaired, but a practice possible with 600 volts would probably be fatal when attempted with the very high potentials now obtaining in single-phase operation.

In this latter system it seems vital in the interests of general safety that every crossing bridge, and every supporting structure should be mechanically and permanently connected with the return circuit of the rails, to avoid the possibility of such structures being in partial or complete contact with the overhead conductors and not absolutely grounded, and at all crossings and highways both the catenaries and the trolley-wire should be thoroughly shielded from either accidental or wilful interference.

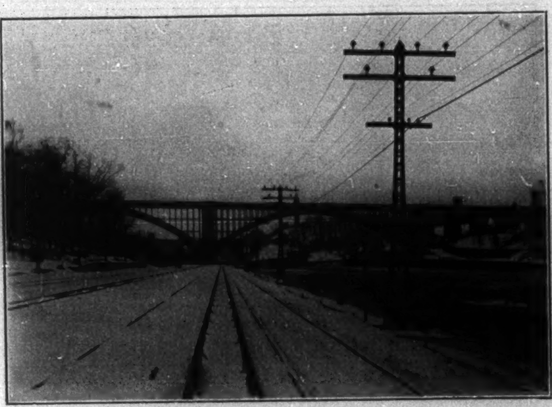


FIG. 29—Protected third-rail buried in snow

The time-honored tickler in universal use on steam railways to warn freight brakemen of the proximity of highway crossings, bridges, and tunnels seems unavailable with an overhead system; because if it did not catch in the pantograph collector it would be an ever present menace not only in wet but also in dry weather, because of the possibility of it coming in contact with the overhead line.

Where single-phase alternating currents are used, the magnetic and static inductive effects on telephone and telegraph circuits cannot be ignored, nor the danger of interference with signal systems disregarded.

The attitude of city authorities may in time raise effective obstacles to the use of overhead wires except where all crossings pass beneath the line of the road, and will I think, ultimately require new third-rail construction to be fully protected—even although on a private right of way.

Relative direct-current potentials in overhead trolley and third-rail. Now that the improvements in direct-current motor construction, not only those promised but those actually accomplished, have made it possible, quite irrespective of what may be done with alternating-current motors, to use much higher potentials than ordinary—not of course as high as those available in single-phase alternating-current systems—the question sometimes arises: Will not the permissible potential be high enough, taking into account certain other facts, to meet in large measure the demands of railroad operation, whether by overhead or third-rail?

Engineers have generally proceeded on the assumption that the use of a sufficiently high potential for practical purposes is possible only with overhead conductors. In the Siemens-Schuckert installation at Mazières, (Fig. 30) where 2000 volts direct current are used the current is taken from two trolley-wires of like potential supported by cross-wire catenaries from side poles of the same construction as is commonly used to carry the warning tickler.

Again, the third-wire system has been proposed, as on the Krizik road, and, on a recent installation with many grades and heavy tunnels in the Iselle mining district in France, where two overhead trolley-wires are used at 2400 volts, with the track as a neutral, and with the motors grouped in series of two, current being supplied by two Thury generators in series and grounded in the middle.

A comparison of potential relations giving the same losses on three systems is interesting. The systems are:

1. Three-wire, with 2 No. 0000 trolleys, and 75-lb. bonded single track.
2. Two-wire, with same trolley-wires and track-return.
3. Third rail, 70-lb. special, and with same track-return.

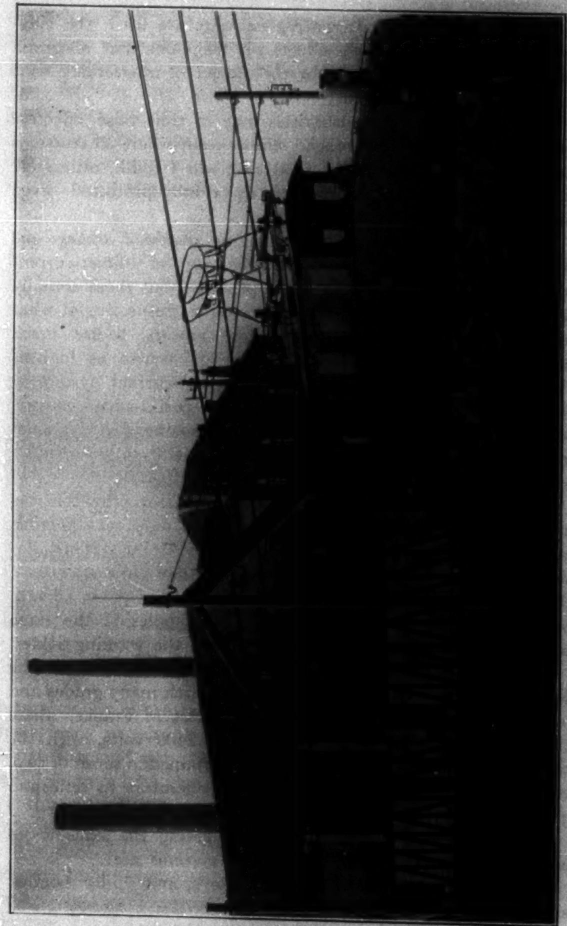


Fig. 30—Siemens-Schuckert 2000-volt direct-current installation at Mazières

The following table gives the comparisons:

System	Resistance per double mile	Ratio of Resistance	$\sqrt{\text{Ratio}}$	Comparative Voltages	
No. 1	0.52 ohms	6.6667	2.58	2400	3100
No. 2	0.165 "	2.1154	1.45	1350	1740
No. 3	0.078 "	1.0000	1.00	930	1200

On such a showing there is little excuse for departing from the lower potentials and the simpler systems, and being handicapped with the higher voltage problems and complication of switches in the three-wire system. If any smaller trolley-wire be used, then the disparity between No. 1 or No. 2, and No. 3 would be emphasized.

The relation of potentials indicated in this table raises the question whether, in view of the disparity of current conducting capacity between an overhead system and the third-rail, it is not also possible that a sufficiently high potential can be used on the latter if from a practical railroad standpoint the balance of advantages and objections should be enough in its favor to warrant its material extension.

Some time ago I stated that in my opinion it was practicable to operate at double the ordinary potentials with a properly protected under-contact sheathed third-rail. I am glad to be now able definitely to announce that it seems possible to construct and operate at these increased potentials with a degree of safety hitherto deemed doubtful. The details of the particular construction necessary must for practical reasons be withheld for the present.

Early alternating-current proposals. In all the discussion concerning direct-current and alternating-current systems, it should be kept in mind that the proposal to operate electric railways by single-phase alternating currents directly is not a novelty, but has had its ardent advocates for a good many years. The late Charles Van Derpoele was one of the earliest to propose this plan; Mr. Ward Leonard has for 15 years advocated the use of a single-phase trolley supplying a motor-generator to operate direct-current motors, a plan often now repeated; and Mr. Arnold attempted the solution by the combination of a single-phase motor operated in conjunction with a pneumatic engine. The Siemens & Halske company conducted the elaborate and costly high-speed Zossen experiments, and the Ganz company have been indefatigable workers in the polyphase field, their Valtellina and Simplon Tunnel installations deservedly commanding widespread attention. Finzi, Winter, Eichberg, La Tour, and others have developed the compensated repulsion type of single-phase motor, and committed themselves to its future. Lamme, Steinmetz, and our American manufacturers have essayed the solution with the compensated series type, at first with 25 cycles, and some now favoring 15 cycles or less.

It is, therefore, incorrect to say that the development is entirely a modern one while that of the direct-current motor has extended over a number of years, for that statement is misleading. Where a score of men were active in direct-current development in the earlier days, handicapped by lack of knowledge and experience, to-day the efforts of hundreds of highly trained men, with all the resources of great capital and manufacturing establishments, have been assiduously directed towards solving the single-phase problem. I think it is safe to say that there is little in its possibilities which has not for some time been fairly well known, and which could not be predicated very closely by theoretical investigation. Nor can I repress the feeling that the same amount of energy, money, and zeal spent on higher potential direct-current developments will produce some remarkable results.

Fifteen-cycle operation. The principal object sought, and certainly a most desirable one in the use of higher potentials, whether direct current or alternating current, is not now so much reduced cost of working conductors on a trunk-line system—for practice has shown that this cost is not materially affected—but lessened feeder investment, increase of sub-station distances, reduction of total sub-station capacity, and, in the single-phase system, the abolition of moving machinery in the sub-stations.

The raising of the potential on direct-current equipments will not be without some objections, not so much, as I have indicated, in the actual construction or use of the third-rail or the overhead trolley, nor because of difficulties in the matter of commutating and grounding, but rather on account of some reduction of capacity because of less slot and winding efficiency where the motors are individually constructed for the higher potentials, this feature being less important if two machines are operated in series. The controlling systems present some added difficulties, but nothing insuperable.

The degree of success of the alternating-current development will depend primarily on the development of capacity and all-round operative features in single-phase locomotive and car equipments. The 25-cycle motor (hitherto the only frequency actually installed for single-phase equipments), whether judged by individual comparison or specific equipments, as I have already illustrated, or the general testimony of electrical engineers of manufacturing companies, has proved inadequate when compared with its rival. To correct this defect it has been proposed to adopt 15 cycles as a standard of operation.

This number of cycles has been under consideration for some time. It is successfully used by the Ganz company in its polyphase installations, it has been proposed in this country by the General Electric and Westinghouse companies for important work, and has lately been urged as a standard by a number of engineers.

Considered solely from the standpoint of the series commutator type of railway motor, a reduction from 25 to some lower compromise number of cycles—15 if you please—has certain distinct advantages; for it should make possible the use of higher field induction, larger air-gap, higher armature potential, slower armature speed, and less sparking—all making for increase of motor capacity for any given weight, and affording greater mechanical freedom in construction and operation. It likewise increases the capacity of trolley and track circuits, and raises the power-factor both of the line and the motor; but against this is an unavoidable increase in the weight of transformers, which, according to such facts as I have at hand, about offsets the saving in motor-weight, It appears, then, that the total weight of single-phase apparatus on a car for a given capacity is approximately the same within a very wide range of variation of the number of cycles. There are, in addition, special objections in the matter of turbine and generator construction, as well as in other directions.

It is difficult to establish exact comparison of equipment weights unless one personally conducts tests, or has complete technical reports which have been made on identical bases; but the following table is one comparison of early estimated weights of complete equipments of two recent typical types of like nominal capacity.

Weight of 4-Motor Alternating-Current Equipments.

Motor	A	B
Cycles	15	25
Nominal capacity per motor	75 h.p.	75 h.p.
Individual Weights:		
Armature	1333 lb.	1146 lb.
Field	2414 "	2646 "
Gear, case, and pinion	398 "	407 "
Total Motor	4145 "	4199 "
Car Equipment:		
4 Motors	16580 lb.	16796 lb.
Transformer and rheostat	6750 "	4325 "
Controller and adjuncts	1000 "	1200 "
Trolley	500 "	500 "
Wiring, switches, etc. (?)	1950 "	1239 "
	26780 "	24060 "
Excess A over B	2720 "	

These totals are not final in either case, for the individual motor weights of each type will very likely be increased from 300 to 450 lbs. in regular manufacture. But allowing for such changes and corrections as seem reasonable, not only is no actual saving in *A* over *B* probable, but the excess of nearly a ton and a half against the 15 cycle equipment will remain in some makes. On the other hand, the manufacturers of *B* hope to show about 10% total saving in the weight of a 15 cycle equipment, but this hope is based upon theoretical estimates, not actual performance.

On other sizes it is probable that these relative differences will vary somewhat, but a comparison of the weight-coefficients of large 15 cycle motors and direct current motors of like weight show a ratio of two to one in favor of the direct current machine.

Motor and locomotive constructions. Motors are of the geared and gearless types, may be entirely separate units or partly integral with the truck-frame, and may be wholly or partly spring-supported. Locomotive designs, influenced in part by the type of motor adopted, show a great variety of constructions, and may be very generally classed as rigid frame with all weight on the driving axles and without leading trucks; rigid frame with either single axle or bogie leading trucks; and bogie-truck locomotives, the bogies being pivoted under the cab, and sometimes linked together.

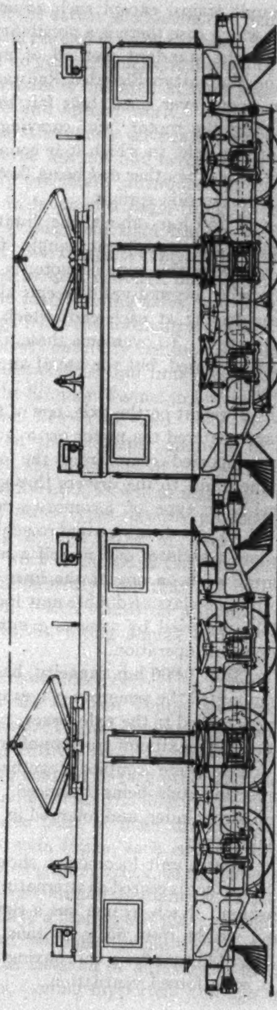


FIG. 31—1500 h.p. double-unit alternating-current locomotive—weight 140 tons.

On all multiple-unit trains, except such as are designed for very high speed, in which case there is a possibility of a gearless-motor development, the standard method of motor-mounting I introduced on the Manhattan Elevated Railway in 1886, and which has been in vogue ever since, bids fair to continue. It provides for centering the motor and carrying a part of its weight upon the driven axle, to which it is connected by any required ratio of gearing, the other end being flexibly suspended from the truck above the side springs.

Up to capacities of 250 h.p., about the limit required and permissible for motor-car equipment, single driving on one end can be used; but when this type of motor is built for larger sizes, in connection with locomotives, it seems almost necessary to provide for gear-driving at each end, which presents some difficulties in construction. To overcome these, the introduction of a spring has been proposed, but the use of an adjustable gear rim seems preferable.

To reduce the dead weight on the axle, one of the French railways some years ago centered the motor on a quill which surrounded, but was supported clear from the axle, connection being made from the quills to the drivers through springs.

The rigid wheel-base type of locomotive without leading trucks is illustrated by an direct-current machine built under the direction of some associates and myself a number of years ago for experimental work on one of the lines running out of Chicago, and also by one class of double-unit locomotives which has been frequently proposed by various companies for single-phase alternating-current operation.

The former, (Fig. 3) of 1,000 h.p. capacity, had four axles, on each of which was mounted the armature of a gearless motor, the field-magnets being attached to the axle-boxes. To insure equal duty on motors, and the maximum tractive effort for its 70 tons of weight, the drivers were coupled together and quarter-cranked, the connecting rods being balanced. The controller was operated by an air cylinder, and followed in time and degree the motion of a pilot lever.

Each half of the double-unit locomotive shown (Fig. 31) has three axles, to each of which is geared an alternating-current motor, after the usual fashion. Each section has a rigid wheel-base of about 12.5 ft., and weighs from 65 to 70 tons, making a total weight of from 130 to 140 tons for a unit having a rated capacity of about 1500 h.p. with forced ventilation.

An analysis of the action of a locomotive demonstrates beyond question that this general type of machine, that is, one having a rigid frame and no guiding trucks, is limited to moderate speeds, and would be unsafe if operated at high speed on a road with much curvature and special work. Notwithstanding the fact that it has been strenuously advocated, even recently, I think this particular type will not find favor among the railroad men, and it is already practically abandoned in the proposals of the manufacturers, in favor of a bogie-truck type, or an articulated type comprising two rigid frames with leading trucks at each end of the complete unit. It is also proposed to carry the geared motors, centered on a spring-connected quill, directly over the main driving-axles, and to support the entire motor by springs from the locomotive-frame.

Particular interest naturally centers upon the distinctive types of locomotives installed on four important railway systems, the Valtellina and the Simplon Tunnel in Switzerland, the New York Central, and the New York and New Haven, which well illustrate three of the principal methods of construction developed to meet the demands of different electrical systems. I will briefly describe each, as well as make some comment upon a few of the many other types recently proposed.

As illustrating a high order of electrical and mechanical engineering, the work of the Ganz Company merits special mention; for it is undoubtedly true that the present status of the polyphase system, which stands on a favored plane with many Italian engineers, is owing almost entirely to the efforts of this company.

The polyphase motor locomotives (Fig. 6) built for the Valtellina Railway and for the Simplon Tunnel are strikingly individual in their construction. The axle mounting of motors is abandoned, the motors being entirely separate units mounted on the locomotive frame, and coupled to each other and the 62-inch driving wheels through an ingenious combination of connecting- and side-rods. Of the three pairs of main drivers, the middle only is journaled in the main frame, each end-pair being journaled at one end of a pivoted guiding truck, at the outer end of which are guiding wheels about one half the diameter of the driving wheels. The end drivers have a limited end play, and one king bolt has a similar freedom of movement, while the other is fixed, resulting altogether in great freedom of adjustment to track curvature. The two motors, spring-supported through the locomotive frame, are each quarter-cranked, and connected to side-rods having downwardly projecting jaws which loosely engage the driving pins of the middle drivers, the centers of which are somewhat below the centers of the motors. On each side of the jaws of the side-rod are coupled the connecting-rods of the outer drivers, provision being made in all bearings for the necessary freedom of movement and adjustment.

In an earlier type, the locomotives were equipped with two sets of twin motors for high and low tension, the low tension to be operated in cascade relation to get slow speed in starting and for running on grades, then to be cut out and the regular running to be with the high-tension motors alone. In the latest machines the twin-motor construction has been abandoned, and the locomotives are equipped with two 15-cycle high-tension polyphase motors, one having 8 and the other 12 poles, and an arrangement of field-circuits in the latter machine such that it can be temporarily made a low-tension motor operated in cascade relation with the other. This combination permits of three regular operating speeds of about 16, 26, and 40 miles per hour. At the lowest speed the motors are in cascade relation, with high draw-bar pull; at middle speed the 12-pole motor is in operation alone on high tension; and at the highest speed the 8-pole motor is used alone, likewise on high tension. Of course, the physical connection of the two motors together and to all drivers makes this method of operation possible. The rated capacity of the motors, as given by Valatin, is extraordinarily high, that with the 12 poles being stated as 1200 h.p. and that with 8 poles, 1500 h.p., based upon the one-hour rise of temperature to 75 degrees. The motors average about 13 tons each.

The use of connecting-rods in this locomotive is not as objectionable as the use of the driving- and connecting-rods in a steam locomotive, because the strains are very different, and the rotative weights can be far more perfectly balanced. It can be fairly said to have the advantage that with the minimum possible weight of locomotive there is no such thing as slipping an individual wheel, a trouble which will occur at times with all locomotives having independently driven axles if equipped with powerful enough motors, because of variation in motor characteristics, track and wheel conditions, and unequal wheel pressure caused by the drawbar pull.

Almost the entire weight of the locomotive is spring-borne, and the behavior of the machine on curves, even at high speeds, ought to be very satisfactory. The same general construction would lend itself very effectively to the application of high-tension inter-pole direct-current motors, and may be very seriously considered in this connection.

The general characteristics of the New York Central type of locomotive (Fig. 4), the Batchelder machine as developed by the General Electric Company, is pretty generally understood, and my description will be limited. It consists essentially of a heavy steel frame in which are journaled four main axles, and which is terminated by pivoted single-axle ponies provided with spring resistance against deflection from the central position. The motors are the gearless type, the armatures being mounted directly on the axles, (Fig. 32) and the bi-polar field-magnets forming an integral part of the main frame; they are, therefore, carried with it by the equalizing springs, and have free motion relative to the armatures. In addition to the regular truck frame, an additional path is provided for the magnetic flux, which passes through all the armatures and field poles in series, by a heavy bar extending the length of the frame, and carried above the motors.

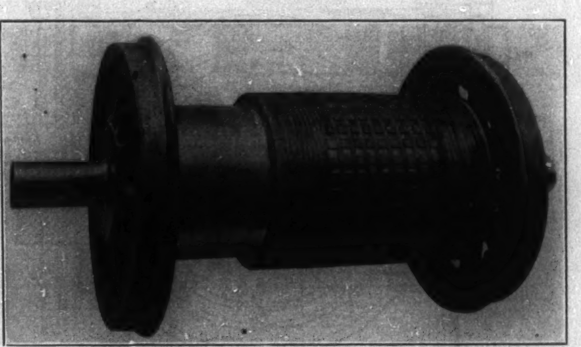


FIG. 32—Armature of bipolar direct-current motor

Being of the two-pole type, (Fig. 33) and with a quadrant winding, the motors are extraordinarily free from sparking tendencies; in fact, they are, structurally, natural 1200-volt machines, although only wound for present operation at 650. So marked is this characteristic, that the brushes, which are 180 degrees apart, instead of being carried on yokes concentrically with the commutator, are carried on arms attached to the field-magnet frame, (Fig. 34) and although moving with it function perfectly.

The electrical and mechanical construction is, therefore, reduced to an acme of simplicity never hitherto attained in electric locomotives, for not only are there no gears, but there are no armature or field bearings, quills, driving-spiders, or special spring connections, although all the weight of the motor except the armature is spring supported.

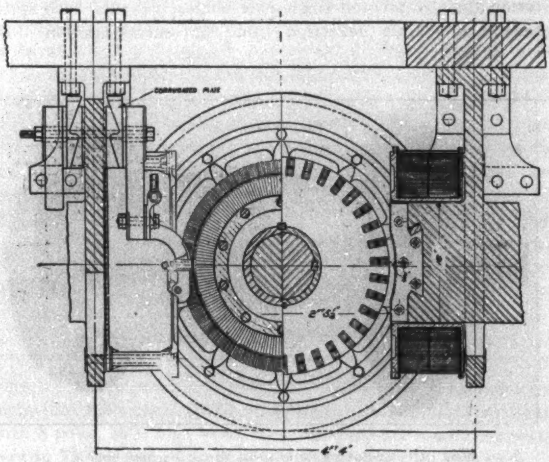


FIG. 33—Longitudinal section—bipolar direct-current motor.

The air-gap is very large, and as the pole pieces are very nearly flat, a complete axle unit with its armature can be readily dropped out, and replaced without disturbing the balance of the motor equipment. This type of machine, of course, cannot be used with any form of alternating current directly, no matter what the frequency.

When first proposed, the design was considered so radical that its choice met with a good deal of criticism, but experimental trials extending over two years, with 67,000 miles of operation, amply demonstrated its remarkable reliability and efficiency, qualities confirmed by the operation of 35 of these locomotives now delivered and in regular service.

The total weight of the locomotive, without heating equipment, is about 95 tons, of which 70 tons is on the drivers. The nominal capacity, with 75 degrees rise and natural ventilation, is 2200 h.p., at which output with 600 volts the motors run at 300 revolutions, corresponding to 40 miles an hour. The rigid wheel-base is 13 feet, the total wheel-base 27 feet, and the length over all 37 feet.

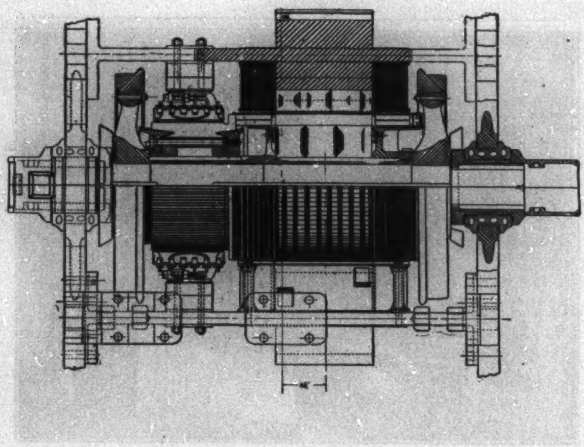


Fig. 34—Transverse section—bipolar direct-current motor

The individual control is the series-parallel bridge method, with resistance variation, the grouping of motors varying from four in series to four in multiple, and current is taken from the under-contact rail by side-extending flipper-shoes.

The original specifications required each locomotive to handle a trailing load of 400 tons on a specified service, two locomotives, under common control by the multiple-unit system, to be used with the heaviest trains on high-speed runs. It is most satisfactory to find that these locomotives have developed an extraordinary emergency hauling capacity, such that there is no train pulled out of the Grand Central Station, into which the first run was made September 30, 1906, which cannot be handled by a single machine at the speeds required within the limits of present operation.

The exigencies of service are responsible for a recent remarkable test of this tractive power. On April 26, the Lake Shore Limited, north bound, consisting of nine heavy Pullman cars hauled by a Central-Atlantic type of steam locomotive, was stopped in the tunnel under 66th street, on a 0.5% upgrade, because of some mishap to the engine. Following it was a train of seven standard day coaches, shop bound and hauled by an electric locomotive, which promptly coupled on to the leading train, and without any assistance from the steam locomotive, which was dead, started the entire load of 16 cars and 2 locomotives, weighing nearly 1,000 tons, with good acceleration, and made the run up a 1.02% grade, a half-mile long, at satisfactory speed and without difficulty.

FIG. 35 —Turbine room, Port Morris power station

Those concerned with the planning and installing of the New York Central equipment justly feel that it is epoch-making in forwarding the march of electrification, and it is gratifying to note that although the electric service was inaugurated only as recently as the 22nd of last December, has been developed under extraordinarily difficult circumstances, and has had to face much adverse criticism because of a serious accident due to extraneous causes, already 305 train movements, representing 86% of the present total of the New York Central and Harlem trains, both locomotive-drawn and multiple-unit, are operated electrically. The aggregate delay has been less than with the old steam service, a fact particularly noticeable in times of snow-storms. The main station (Fig. 35) output for 24 hours is but about 65,000 kilowatt-hours, and when the batteries are in service but one steam unit is required at time of maximum load.

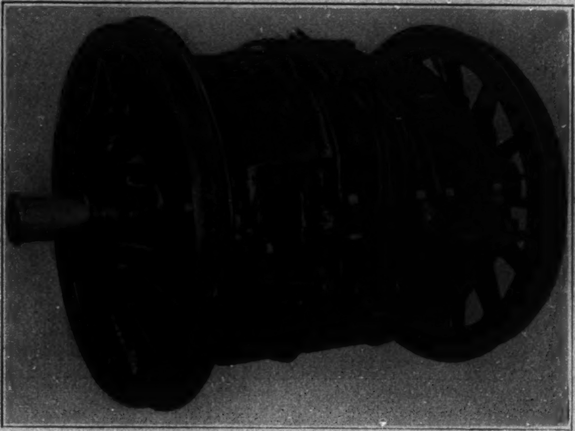


FIG. 36—Motor and axle unit of alternating-current New Haven locomotive

The New Haven alternating current-direct current locomotive, built by the Westinghouse Electric & Manufacturing Company, is of the 2-axle free bogie type, the bogies being pivoted under, and transmitting their effort through the frame which carries the cab, in which are mounted the transformers, blowers, rheostats, and controllers (Fig. 37). On each truck are mounted two spring-supported motors, each complete within itself. The armatures are carried on quills, terminating in spiders at each end, which engage eccentrically wound springs enclosed in pockets in the main drivers (Figs. 36-39).

The rigid wheel-base is 8 feet, the total wheel-base 22 feet, and the length over all 37 feet. The weight of the locomotive is 93 tons, having been raised considerably over early expectations. It has an hour rating, on the usual standard, of 1,000 h.p. when operated at 25 cycles, but is equipped with blowers to raise the average capacity. It is intended to handle a 200-ton trailing load at schedule, with some margin of performance.

Although built primarily for operating directly from 11,000-volt single-phase alternating current, these locomotives must operate also from the 650-volt direct current while on the Harlem tracks. They, therefore, have additional control provision, and besides the double-pantograph collectors, have contact shoes, those on the side being arranged for lifting by air pressure on account of limited clearances on a part of the run.

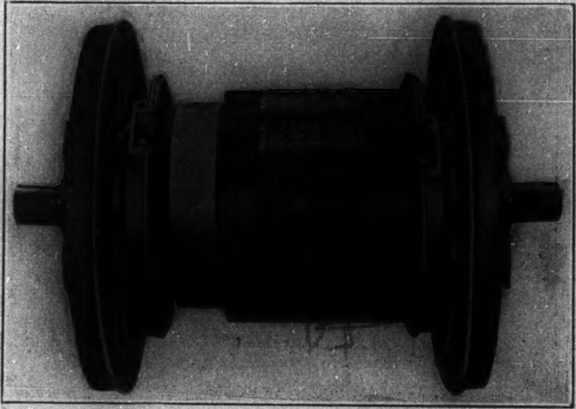


FIG. 37—Armature bearings and axle unit of New Haven alternating-current locomotive

The motor armatures are wound for operation at a normal maximum of about 235 volts, and hence are connected in permanent series of two, while the field-circuits are arranged for each pair of motors in a separate group, and for series-parallel grouping independently of the armature circuits, to provide for the varying flux in alternating-current and direct-current operation. Of course, the two motor groups can be connected for series-parallel operation with direct-current supply, but with the disadvantage of using about double the amount of current at slow speeds that is required when four motors, each wound for the full potential, are in series.

The first of these machines, pulling a short train, made entry into the Grand Central Station on May 11, 1907, and in a short time the operation of equipment should be under service test.

Some question has been raised as to whether trucks with drivers of so large a diameter, 62 inches, on which are concentrated 15 tons of motors in a limited wheel-base, will track properly under all conditions of rail. Experience, however, is the final criterion.

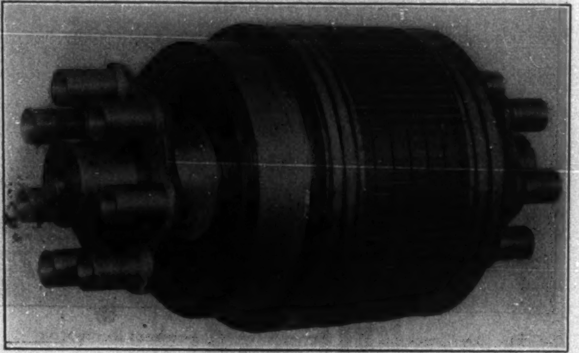


FIG. 38—Armature and driving spider of New Haven alternating-current locomotive.

In order to combine the possibility of single-phase alternating-current current transmission at high voltage by overhead trolley, and the unquestioned advantages of the direct-current motor, it has several times been proposed to introduce between the line supply and the motors a motor-generator set, comprising an induction motor taking current directly from the line, and driving a continuous-current generator to supply the motors, this converting set being carried in the main cab, with provision made for the extra weight by bogie trucks at each end, (Fig. 41) or in an independent tender taking the place of the steam tender in existing steam practice (Fig. 40). Of course this is the introduction of a moving sub-station individual to the locomotive which is operated by it, and makes the latter subject to all the idiosyncrasies of the intermediate apparatus, besides laying up an enormously expensive machine in case of any special trouble. Where the motor-generator set is carried in a separate tender, this disablement only cuts out a part of the equipment, which can be replaced by another like part, but in any case it is debatable whether such a moving sub-station offers any advantage over the stationary one.

Sometime since, I made a very careful investigation of the possibilities of direct-current gearless and geared motors, (Figs. 42-43) the former of the bi-polar type, for identically the same service, a very severe one.

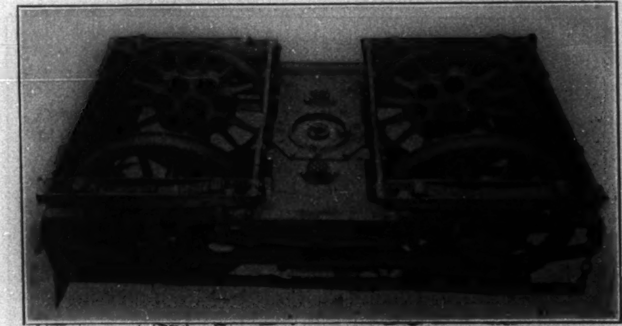


FIG. 39—Truck of New Haven alternating-current locomotive.

Both machines are of the four-axle bogie-truck type, the trucks being linked together. The geared locomotive weighs 93 tons and the gearless 126 tons, but the weight per axle is well within the usual allowance. On each truck are four motors, connected two in series, to be operated at a maximum line potential of 1500 volts. The geared motor construction is of the usual standard, but fitted with commutating poles, while the gearless machine has modified bi-polar motors of the N. Y. Central type.

A comparison of the efficiency curves of the two machines is interesting, these showing for each from 87 to 88% on a five-hour load, and falling only to 83% with 50% increase, while at

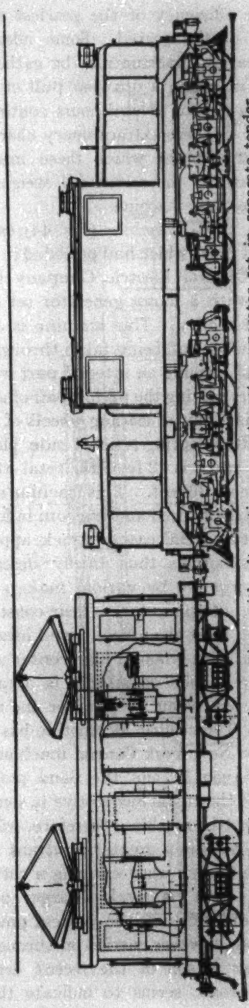


FIG. 40—Direct-current locomotive, with alternating-current motor-generator set in separate tender.

half this load the efficiency of the gearless machine is much higher than that of the geared. Some adequate idea of the capacity of the gearless machine may be gathered from a statement that it will maintain a drawbar pull of nearly 25,000 lb. at a good rate of speed for several hours continuously, and with natural ventilation. These extraordinary characteristics would, for the class of service for which these machines were considered, amply warrant the additional weight because of the simplicity of the gearless machine.

A very promising type of machine (Fig. 44), embodying many of the good features of those which had preceded it, is now under construction by the General Electric Company, for use either on direct current, or with a motor-generator set supplied from an alternating-current trolley. This machine is of the 4-axle free bogie type, the drawbar pull being taken through the main frame. On each truck, and forming an integral part with it, are two bipolar gearless motors driving the middle pair of axles, and at either end of each truck is a pair of leading wheels of smaller diameter, which have a limited, spring-resisted side play. The normal wheel-base of each truck is 12 feet, the total wheel-base 32 feet, and the length over all 36 feet. This machine should be capable of an almost unmatched speed and freedom in following irregular curvatures, and with special ease of track approach.

The various locomotives thus briefly described are but a fraction of those proposed by various makers to fit particular conditions and types of apparatus. Their construction does not, in many particulars, meet the preconceived ideas of some steam-locomotive builders, with whom a high center of gravity and all the weight possible carried on springs is a cardinal principle, and a very correct one when we consider the necessities of the steam locomotive. The electric locomotive has a lower center of gravity, that of the New York Central machine being about 44 inches, the New Haven 51, and the Ganz probably somewhat higher, while that of the steam locomotive is sometimes as high as 73 inches. The electric machine, therefore, will have less tendency to topple over, but a greater resultant side pressure in case of irregularity of track when entering a curve, or running on an irregular track, than its rival, a larger portion of whose weight heels over and increases the vertical pressure on the rail. Careful investigation, however, carried on through many sources, and inaugurated by reason of the recent derailment on the New York Central road, seems to indicate that with electric

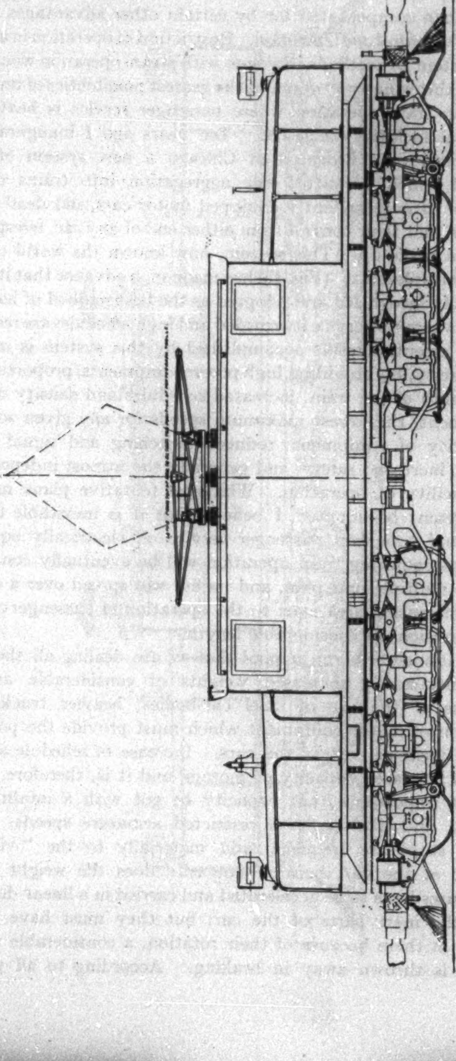


FIG. 41—1500-h.p. alternating-current locomotive, with gearless direct-current motors and motor-generator set. Weight about 160 tons.

motors properly guided any increased tendency to side-thrust is more than compensated for by certain other advantages

Train Control and Operation. Restriction of operation in an electric system to methods in vogue with steam operation would be a useless throwing away of one of the geatest possibilities of improvement in train operation where passenger service is heavy and terminal facilities congested. Ten years ago I inaugurated on the South Side Elevated of Chicago a new system of train control, which permitted the aggregation into trains of any number of independently equipped motor cars, and dead cars if desired,,and their control from either end of any car, irrespective of train make-up. This system, now known the world over as the "multiple-unit," (Fig. 45) has made such advance that it is now generally recognized and adopted as the best method of handling trains wherever service is crowded and high schedules are required.

The essential result accomplished by this system is increase of capacity, by providing high power equipments, proportional to the length of the train, increased schedules and density of train movement, the lowest maximum speeds for any given schedule similarity of equipment, reduced switching and signal movements, increased safety, and generally the utmost independence and facility of operation. Whatever tentative plans may for the present be adopted, I believe that it is inevitable that all local and suburban passenger service on electrically equipped railways requiring train operation will be eventually conducted on the multiple-unit plan, and its use will spread over a continually increasing area, even to the operation of passenger cars run over divisions of considerable length.

But it must be borne in mind that we are dealing all the while with necessarily increased weights of considerable amount, because of the use of steel car-bodies, heavier trucks, and addition of motor equipment which must provide the power to propel itself as well as the cars. Increase of schedule also demands increased capacity of motors, and it is, therefore, of the utmost importance that capacity be got with a minimum of weight, and likewise with restricted armature speeds, which, where stops are frequent, add materially to the "virtual" weight of the car; because not only does the weight of the armatures have to be accelerated and carried in a linear direction with the inert parts of the car, but they must have energy stored in them because of their rotation, a considerable part of which is thrown away in braking. According to all present

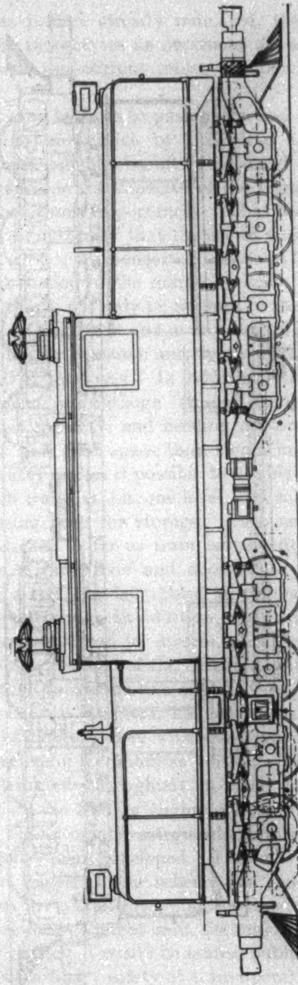


FIG. 42—1800 h.p., 1500-volt bogie truck locomotive, geared motors. Weight 93 tons.

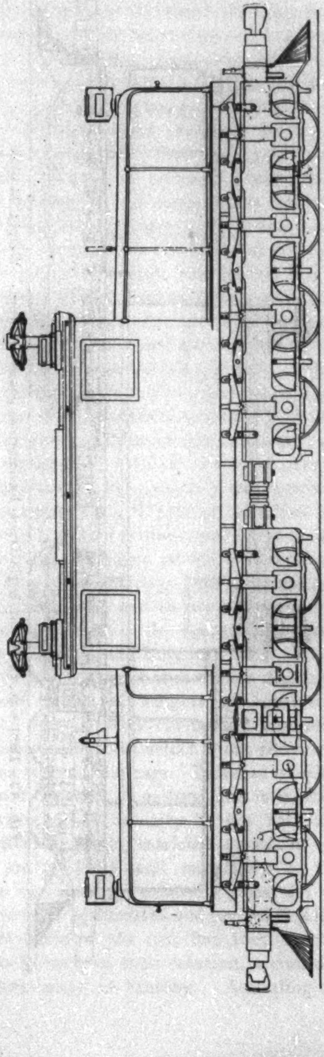


FIG. 43—1800 h.p., 1500-volt bogie truck locomotive, gearless motors Weight, 126 tons.

developments, as I have already indicated, the direct-current equipment has in this service an enormous advantage over any single-phase alternating-current motor equipment with its car transformer.

Irrespective of the benefits to passengers, and the influence in building up suburban service by providing a high schedule train system which can be absolutely adjusted to the needs of traffic, the influence on the capacity of the terminal facilities of a railway is of the utmost importance. It has been declared by a competent English authority that the use of multiple-unit trains in the suburban service of a congested station at least doubles the capacity of that station in the matter of track movements and the dispatch of trains, not only on account of the ability to operate the trains from any point and in any length, but also because of halving the number of switch and signal movements necessary where locomotives are used. In addition, the electric locomotives necessary on through trains, being double-ended, compact for their capacity, and needing no turn-tables, occupy much less track and yard space than steam machines. Again, the use of electricity makes it possible to double-deck a terminal, bringing through trains in on one level, and suburban trains on another, and using both for storage. As a net result, it may be safely stated that so far as train movements are concerned, the capacity of a yard, over and above that required for the storage of cars alone, can be trebled as compared with steam-locomotive-drawn trains. In addition, the yards can be roofed over, and the space utilized for streets, parks, or buildings.

The remarkable extension of the multiple-unit system, and its recent application to locomotive practice, as for example on the New York Central Railroad, has led to the suggestion that freight trains shall be equipped with secondary controlling lines, and that a plurality of locomotives, not only at the head of the trains but distributed throughout it, shall be handled by a single operator on the leading engine, whose controller shall be provided with the automatic safeguards common to the service which has already been developed. I do not hesitate to pronounce this an impracticable scheme for general application. Quite aside from the cost of equipping the hundreds of thousands of rapidly deteriorating freight cars, the majority of whose train lines would not be used, it would be against public policy, and contrary to the most ordinary safety of train operation, to leave such an extended and high-powered train in charge of a single man.

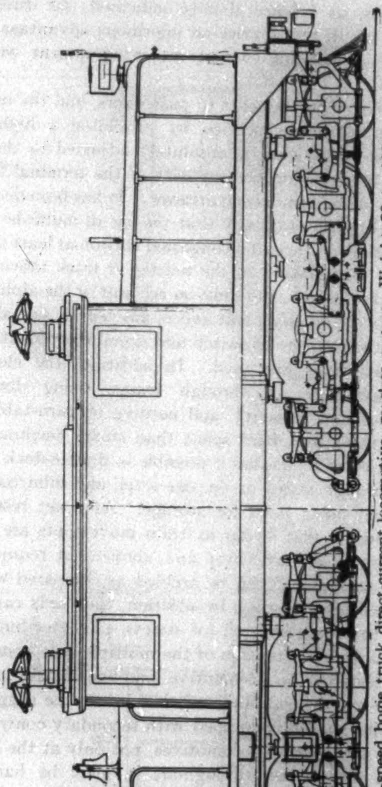


FIG. 44—High-speed bogie truck direct-current locomotive, gearless motors. Weight 80 to 110 tons.

Locomotive operation is distinctly different to that on elevated and underground roads, and the operators make their runs under widely varying conditions. The handling of a long freight train is entirely unlike that of a train made up principally of motor cars; it has to be coaxed, favored, and nursed, for scarcely any two starts are alike. As useful as automatic controller advance is with the ordinary multiple-unit train, and even admitting, which is debatable, the advisability of connecting up the air-brake with the control, it is safe to say that in ordinary freight operation these features should not be added to the controller, and if they were the engineer in time would beat them.

While double-headers under a common control will undoubtedly be used when necessary on both freight and passenger trains, when one considers all the varying conditions of trunk-line operation, neither public policy, safe railroad operation, nor if you please, labor conditions, would permit the handling of a train with two or more locomotives so coupled up, with only one man in the cab. It should not be permitted even with a single locomotive, and I do not believe that any man who has had practical experience in riding locomotives will long continue to endorse any such proposal.

Storage-batteries. The use of the storage-battery in connection with electric railway operation is a proposal concerning which much may be said, for and against, depending largely upon what value one attaches to restriction of peak-loads on moving machinery and to insurance. That it has been, and is being used successfully in connection with direct-current equipment of moderate potential admits of no dispute, and it has been stated that it is equally available for alternating-current installations. This latter claim is misleading. On direct-current systems the principal function of a battery is that of an equalizer. If installed at a central or sub-station it is usual to provide boosters to govern the charging and discharging. These, however, are only of differential watt capacity, and while they are necessary for regulation, it is perfectly possible to use the battery in some emergencies by direct connection with the line. Sometimes the battery is used at an auxiliary sub-station without any boosters whatever, the charging and discharging being determined by the drop on the line, or by the use of an extra feeder.

With an alternating-current system, the battery at a substation plays an entirely different role. It must be charged by a

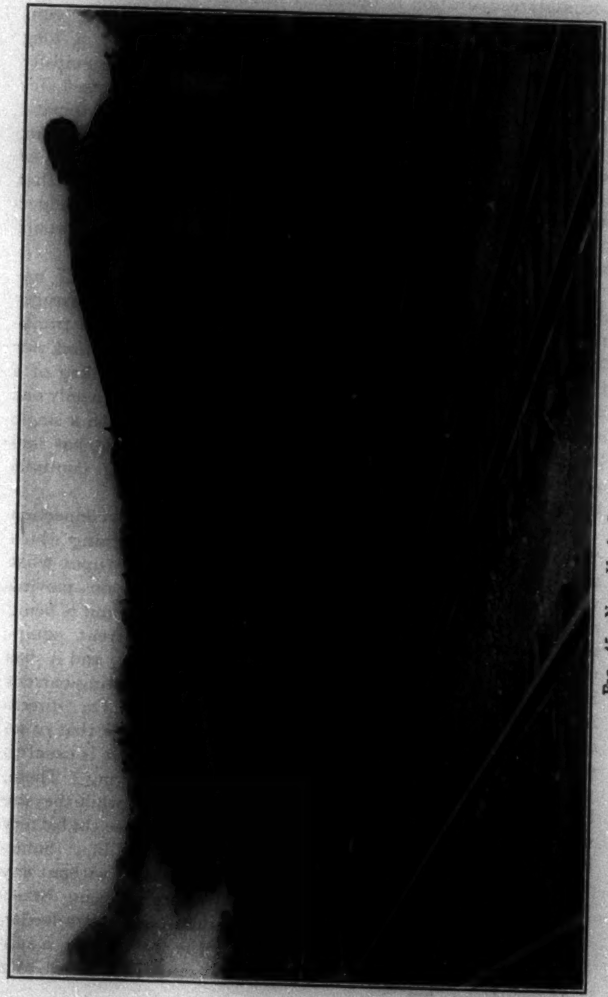


FIG. 45—New York Central multiple-unit train.

direct-current generator driven by an alternating-current motor, and in discharging drives the alternating-current motor as a dynamo through the direct-current generator acting as a motor. In addition to the introduction of moving machinery in an alternating-current sub-station, its watt capacity must be equal to that of the full discharge of the battery, and the latter can have no function in supplying current to the working conductor except through the medium of two rotating machines of large capacity.

Where current is purchased from a water-power plant, and it is necessary to change frequency as well as restrict the peak-load by which charge for power may be regulated, the battery may be used in combination with an alternating-current motor, a single-phase generator and a direct-current machine; the alternating-current motor driving the single-phase generator and the direct-current machine to charge the battery when the load on the line is light, and the alternating-current motor and the direct-current machine, operating as a motor supplied by current from the battery, together driving the generator when the load is heavy.

Use of step-up and step-down transformers. Where the distance is not great, as on the present proposed limited operation of the New Haven road, both step-up and step-down transformers have been omitted, and the 11,000-volt trolley-line is supplied from the station switchboard. This means direct connection between an extended system of overhead working conductors and generators operated at high potential, with one side grounded, with, of course, whatever protection lightning-arresters can provide. Such are the vagaries of lightning and the uncertainty of the very best arresters, that I cannot but feel that this practice, which subjects costly generating equipments to direct lightning attack and special grounding stress, will not obtain to any great extent; for the possibility of laying up a complete unit of great capacity, steam engine as well as generator, because of a lightning flash or accidental ground, is too great a penalty to pay for eliminating transformers, and is a special handicap upon the possibilities of transmission.

It is certain that standardization should be directed to the construction of generators. Any material increase of potential above that now common means reduced capacity and efficiency, increased danger of breakdown, and greatly increases individual cost, to say nothing of the capitalized risk of failure. Quite aside from the question of cost and efficiency, air cooling, the only possible method for generators, manifestly cannot be safely carried above that which is tolerable for static transformers, which, when wound for the higher potentials, are invariably oil-cooled. Therefore I expect to see standardization of generator potentials, the pressure being stepped up by transformers to whatever transmission potential is necessary, and then stepped down to the working pressure on the trolley-wire if alternating current be used, or to a lower pressure and converted if direct current be used.

The transformer, *per se*, is the simplest and most flexible device for changing alternating-current volume and pressure, and its moderate cost and high efficiency, taken in connection with the like elements of moderately high potential generators, will leave the total cost and efficiency of generating equipment roughly the same. There will be the added very great practical advantage that the generators not only work at lower potentials, but on closed metallic circuits, are removed from direct contact with working conductors and earth, and have interposed between them and the line at least one set of static transformers, which practical experience has shown to be one of the best generator safeguards against lightning, and which, if broken down do not involve large and costly units, nor wholesale sacrifice of capacity.

General cost comparison of direct-current and single-phase alternating-current systems. Summarizing briefly, the alternating-current—direct-current and the single-phase alternating-current systems have certain features in common, and others differing, which may be briefly stated as follows:

Each must have a central station, which in the former will generate three-phase currents delivered to step-up transformers to raise the voltage of the transmission lines to any required degree, while in the latter, single-phase currents will be generated at a practical potential, and likewise stepped-up for transmission. Assuming equal kilowatt outputs, the generating part of the three-phase system will be cheaper than that of the single-phase, because of the higher weight-efficiency of the polyphase apparatus; but the switching devices will be somewhat more costly, while the transformers will cost about the same, with the net result that the cost of installation per kilowatt, and with equal conditions in the matter of speed, reliability, and efficiency, will be somewhat less for the polyphase than for the single-phase equipment.

The transmission lines, especially where provision is made for duplicate or reserve circuits, may for the purpose of this general comparison be roughly considered as of equal cost.

Sub-station transformers must be provided on each system to lower the transmission to the operating or transforming voltages. There will be approximately an equality in these features.

Just here is a line of departure, the transformed current in the alternating-current—direct-current system being passed through synchronous converters, and delivered to either an overhead trolley or a third-rail, assuming for this purpose the latter, while in the single-phase system it is delivered to an overhead trolley. The converters and the necessary housing and switching apparatus is an excess cost chargeable to the older system.

We come now to the working conductors of the two systems. The third-rail, which is prohibitive to the alternating-current system, cannot be put in except on what may be fairly called a permanent basis, at a certain approximate cost per mile of track equipped. The overhead trolley for the alternating-current system can be put in on either of two plans, one more or less tentative and temporary, using wooden poles and wire suspensions; the other, which is practically the only way affording reasonable permanence, with steel poles or bridge supports. Under this latter condition of permanence, the cost of such an overhead system per mile of track will run fully as high, and in many cases higher than the cost of the third-rail installation.

The costs of section-houses, circuit-breakers, and automatic apparatus will be quite as much with an overhead system as with the third-rail.

Tracks in either case must be bonded, more heavily and hence at greater expense for the direct current than for the alternating, but the difference will often be met by features connected with the overhead system, such as extra cost of piers, pull-offs columns, changes necessary in telegraph and telephone circuits, and clearing the right of way from trees.

The remaining element is the locomotive and motor-car equipment; the motors for the direct-current system being operated on the series-multiple plan, with resistance variation and possibly with field shunts, those for the single-phase alternating-current system, except where there is the intermediary of a motor-generator set, through a secondary or autotransformer carried on the car. According to present developments, there is here very great difference in the weight and cost of apparatus, and in the number of motors necessary to perform any given service. Judged from every standard which I have been able to compare, the cost of this part of equipment with 25-cycle alternating-current motors is so much higher than that with direct-current motor equipments, that, assuming a reasonable operating potential on the third-rail, it is certainly a debatable question whether the increased cost, and cost of operation of the motor-car equipments will not fully offset the cost of the synchronous converters and the losses in their operation.

I have made many comparative analyses, involving millions of dollars, and I have found that where equal permanence of installation is provided for, and equal ultimate as well as average duty, there is not on demonstrated facts a very wide variation in the initial cost of plant.

Ordinarily, the signal systems used on railroads will have to be changed at considerable cost. Fortunately, methods have been developed which permit the use of all the rails for the main return-circuit by using a special alternating-current circuit for operating the signals. Where the tracks are used for direct-current return, reactance bonds are inserted which permit the flow of the direct current, but resist that of the alternating signal current. Where the tracks are used for alternating-current operation, and are likewise subject to the flow of direct currents, the signals must be operated by alternating currents of high frequency through apparatus which is inoperative to currents of low frequency or continuous currents.

Field of the single-phase alternating-current motor. It would be idle to deny, and I have no wish to belittle the good work done and the results achieved in the development of the single-phase motor, just as it would be equally unwise to ignore what has been done in polyphase and direct-current work. The results, whatever they are, are facts which must be dealt with in a judicial spirit; but facts, not contradictory and unwise or unsupportable claims, must eventually guide the engineer. No one can deny that if the single-phase motor be developed to a high state of weight-efficiency, unhandicapped by excessive weight of the collateral apparatus necessary on a car to utilize it, and if the capacity of conductors, especially steel conductors, for alternating currents can by any discovery be raised, the elimination of moving machinery in, and the simplification of sub-stations would open up a very extended and important field for the use of this type of apparatus.

But with developments as they are at present, what is the actual field? As there is no general agreement as to methods of construction, so, too, I find no fixed conclusions as to the field of commercial usefulness; rather, on the contrary the sharpest differences of opinion. Some, with enthusiastic catholicity, make it all-embracing for steam roads, quite irrespective of well known limitations. Others, although at times seemingly contradictory, are even more elastic in their claims.

For example, one engineer says: "It is recognized that for heavy railroad service, where all kinds of speeds should be obtained economically, the single phase railway system will undoubtedly show to great advantage compared to any known continuous current system." Again, the same authority states: "While suburban work was once thought to be the most important field for the single phase railway, it has now become evident that city work, where traffic is very congested in parts of the system, will prove to be one of the best fields." Another affirms: "Interurban electric traction work is the peculiar field of the alternating current system," but adds to this the statement: "When stops are few, the advantage of the alternating-current system is not so greatly marked. In short runs, the alternating current system can have the greater advantage."

It has even been stated that for such services as that on our elevated and underground rapid transit roads, with their congested train movements, quick accelerations, high schedules and limited clearances, the single phase alternating current motor would find a fruitful field. It would, but the fruit would be somewhat bitter.

It seems to me that the present principal field of usefulness of the single-phase system is on roads of considerable extent which operate an irregular and sparse traffic, and where only a moderately expensive, or what may be called a second-class overhead construction, which will keep down the ratio of line investment to that of the balance of equipment, is tolerable. As one departs from this condition, adopts more permanent construction, and faces the problems of denser traffics and higher capacities, any advantages of the single-phase system will disappear, and the superiority of the direct-current equipment, with such improvements as are in sight, become manifest. But whatever may be the future of single-phase operation under the conditions stated, any present claim for it as the preferable equipment for congested service demanding high schedules and great capacity is not worth a moment's thought, for in this field, at least, it cannot touch the direct-current system.

Without individual comment, I quote from the preface of the recent work by Messrs. Parshall and Hobart, "Electric Railway Engineering," the following interesting expression of opinion: "In our judgment, the limitation of the alternating current motor is fixed, in its relation of energy output to weight, by the inherent properties of single-phase commutator apparatus, and the limitation of the continuous-current motor will be determined by the maximum safe voltage at which a commutating machine can be worked. While the development of each class of machine has advanced beyond the point that could reasonably have been foreseen, and while it is impossible at the present time to predict where the limitations will be reached, we are satisfied that a careful comparison of the two types at the present time is decidedly to the advantage of the high tension continuous current motor."

In closing, let me again remind you that we engineers are not omniscient, or immune from mistakes. Feeling strongly and speaking confidently of those things in which we believe, it is not reasonable to assume that the great diversity of opinion which exists, often emphasized by individual experience along specific lines, reinforced by knowledge of what has been accomplished in other directions, and influenced by such personal bias as we are all subject to, emphasizes the necessity of the utmost development in every direction; and the probability, nay certainty, that there is at present no single system which can be selected as best for all purposes, but rather, that a wide and increasing use of each will be created, and in the majority of cases a compromise selection of the best elements of alternating- and direct-current practice will obtain.

While there are many things in railroading which have been standardized, and others which can now very properly be, and which of themselves do not militate against the independent judgment of operating railway officials in matters individual to their own systems, I think it is certain that these same officials will in the future, as in the past, consider the problems involved in a change of motive power from steam to electricity from an individual standpoint, and that they will demand from manufacturers, as well as from their engineers, all possible freedom from restriction, exercising in a large measure their own judgment as to the adoption of any system. I see no practical necessity to formulate conclusions by averaging conditions, and I cannot conceive the responsible officers of any trunk-line road being guided in their determination of what seems best for their own requirements by consideration of what some road thousands of miles removed in location, and enormously differing in operating conditions may do.

In any case, the most satisfactory system will be that one which will permit of continuous all-round operation under such conditions as will utilize to the utmost all the beneficial features of electric application. If any one system can be demonstrated to meet these conditions better than all others, then that system will become preeminent, no matter what standards may have been adopted or recommended, and no matter what our preconceived prejudices may be.

APPENDIX.

Among the publications containing my views on the subject of heavy electric traction, may be mentioned the following:

National Electric Light Convention, Feb. 1890. Paper on "The Electric Railway."

Forum, Sept 1891. "The Future of the Electric Railway."

American Institute of Electrical Engineers, June, 1892. Inaugural Address: "Coming Developments of Electric Railways."

Engineering Magazine, July, 1895. "Will Trunk Lines be operated by Electricity?"

Electric Power, Nov. 1895. Editorial Views on Replacing Steam Locomotives by Electricity.

Engineering Magazine, Feb. 1898. "The Possibilities and Limitations of Electric Traction."

American Institute of Electrical Engineers, Feb. 1900. Discussion of Boynton's paper: "Electric Traction."

Electrical Review, Jan. 1901. "Historical Notes of Electric Traction."

Institution of Electrical Engineers, Feb. 1901. Discussion of Langdon's paper: "The Supercession of the Steam by the Electric Locomotive."

Engineering Magazine, Oct. 1901. "The Rapid Transit Problem in London."

American Institute of Electrical Engineers, June, 1902. Discussion of Arnold's paper: "Relative Costs of Operating by Steam and Electricity."

Electrical World, March, 1904. "The Past, Present and Future of Electric Traction."

International Electrical Congress, St. Louis, Sept., 1904. "The History and Development of Electric Railways." Discussion of Arnold's papers: "Electrification of Steam Railways," and "Polyphase and Single-Phase Traction."

Discussion of Dawson's paper: "Electric Traction on British Railways."

New York Railroad Club, Jan., 1905. Discussion of Potter's paper: "Developments in Electric Traction."

American Institute of Electrical Engineers, Feb., 1905. Dinner celebrating Triumph of Electric Traction; "The Art and The Men."

Century Magazine, July-August, 1905. "The Electric Railway."

Street Railway Journal, Oct., 1905. An Unprecedented Railway Situation."

New York Railroad Club, March, 1906. Discussion of Lamme's paper: "Alternating-Current Electric Systems for Heavy Railway Service."

American Institute of Electrical Engineers, Jan., 1907. Discussion of Stillwell and Putnam's paper: "The Substitution of the Electric Motor for the Steam Locomotive."

DISCUSSION ON "SOME FACTS AND PROBLEMS BEARING ON ELECTRIC TRUNK-LINE OPERATION," AT NEW YORK, MAY 21, 1907.

W. J. Wilgus: There are so many points on which I fully agree with Mr. Sprague that it is perhaps well at the outset to dwell on one matter where we appear to disagree, and that is the relation of those engaged in the conducting of trunk-line railroad operation to the electrical engineering profession which is now gazing with hungry eyes on that enticing field of new endeavor—the electrification of trunk-line railroads. Without intending to indulge in the sarcasm and pessimism ascribed to our friend, the editor of the *Railroad Gazette*, I do believe with him that the cause of electrical engineering would be much more rapidly advanced if an effort could be made to bring the steam railroad official more closely in touch with the practical side of the application of electricity to the art of transportation. It is true that in the past the majority of steam railroad men have rather looked upon electric railroads as beneath their notice, but recent important developments in the change of motive power on some of the more prominent railroads of the country have dispelled this idea; and I feel certain that all steam railroad officials are now looking upon the future possibilities of the electrification of steam railroad traffic with keen interest and with a full appreciation of the magnitude and dignity of the problem.

Unfortunately they have so far felt barred from an intimate study of the subject because of the befogging of their minds by heated claims and counterclaims of the merits and demerits of various electric systems, coupled with the use of technical phrases with which they are entirely unacquainted. After all, the main features of the electrification of steam railroads are understandable to steam railroad men if technicalities can be avoided and the essentials described in ordinary homely language that can be grasped by the men not versed in the technique of electrical engineering. I therefore venture the suggestion that in general discussions intended for the enlightenment of the non-technical steam railroad men, the subject be treated as broadly as possible, with an absence of partizanship and with the use of plain non-technical terms. Furthermore, I believe that it would be conducive to the best interests of the electrical engineering profession to attract practical steam railroad men to a discussion of papers bearing on the electrification of trunk-line railroads so as to secure an interchange of views.

With respect to the conditions that will justify the use of electricity as a motive power in trunk-line operation, I believe that *evolution* will govern rather than *revolution*. In other words, there will be no sudden general substitution of electricity for steam as a motive power, any more than there was as a sudden jump from the small locomotive of the DeWitt Clinton type to the Mallet compound of to-day. Railroads, like all other human achievements, cannot stand still; they must either move forward or backward. It is generally recognized that their ability to move forward is now limited with steam locomotive practice, and that the overcoming of the defects inherent to the steam locomotive can only be accomplished by the use of electricity. It now looks as if the first movement in this process of evolution is the substitution of electricity for steam in congested passenger terminals at large centers of population where the public demands a cessation of nuisances incident to steam locomotives, and where the increasing volume of traffic requires increased capacity that cannot be obtained with the present motive power. The success of the New York Central installation in both of these particulars is an illustration of what can be accomplished, and imitation will surely ensue at other places where like conditions exist. Coincident with the change of motive power in crowded passenger terminals, is coming the use of electrically propelled trains on existing steam-railroad tracks between large centers of population where frequent units are necessary to accommodate the public. We already have an instance of this in the electrification of the West Shore passenger traffic between Utica and Syracuse, a distance of about 50 miles. I addition to these instances, where at this time the wisdom of th adoption of electricity as a substitute for steam is self-evident, there are a number of places in the West where the capacity of steam locomotives of the highest type is entirely inadequate to handle freight traffic on the pusher grades, and the only manner in which the increased capacity can be obtained is by means of electricity. With a start in the substitution of electricity for steam in the operation of congested terminals, connecting lines between large centers of population, and long pusher grades with heavy freight traffic, we may look with confidence to a gradual expansion of the use of the new motive power in other directions. For example, in the case of the New York Central the primary object of the use of electricity was to abate the smoke nuisance in the Park Avenue tunnel and to increase the capacity of the Grand Central terminal. When this decision was reached, it became self-evident that the use of the motive power should extend to the end of the suburban territory at Croton on the Hudson Division, a distance of about 35 miles. While the northerly terminus of the main line is thus planned for the present at Croton, it is probable that just as soon as the developments in the electrical field will warrant such action, the electric zone will be extended as far as Albany, a total distance of 142 miles.

This brings up the question of the respective merits of the three electrical systems now warmly advocated by their respective friends; videlicet, the direct current, single-phase alternating current, and three-phase alternating current. Looking at the matter from an electrical standpoint, it is very much to be deplored that the advocates of each of these systems have seen so much to condemn in the others, as this practice has frightened the steam railroad men from taking any decisive steps when there is such disagreement among those upon whom they must depend for guidance. If instead of blindly teaching the merits of one system to the exclusion of others, the electrical engineers could unite upon the axiom that each special condition should be carefully studied and the system adopted best suited to it, I feel certain that the cause will be further advanced. For instance, direct current was adopted for the New York Central installation at New York, among other reasons, because the clearances in the Park Avenue tunnel and the ordinances of the City of New York absolutely precluded the use of overhead construction; and yet we are told that a great mistake has been made and that no other system should have been used but single-phase alternating current with overhead construction. Entirely apart from any arguments, pro and con, of the relative merits of the two systems, it will be seen that physical and legal conditions prevented the adoption of any system other than the direct current. When there are no limiting conditions, and the steam railroad engineer is free to give full sway to the exercise of his judgment as to the selection among rival methods, he asks first, which is the most *reliable*? Accustomed to the use of long-tried steam locomotives, the breaking down of any one of which does not necessarily affect the movement of many others on the line at the same time, he naturally looks askance at the adoption of a new method of moving trains that carries with it the danger that in case of a disturbance at the power station or transmission lines, every train on the line will come to a standstill.

This question of *reliability* is much more important with a trunk-line steam railroad carrying passengers from remote points, and mail and express from over all the country, as well as suburbanites, than with local street-car systems. For this reason the conservative steam railroad man does not feel like making experiments with untried systems, no matter how alluring their advocates may make them, but prefers to select from systems which by long tried experience are proved to be thoroughly reliable. In fact on the more important trunk-line installations storage-batteries are now felt to be a necessity, not only to provide for violent fluctuations of load much greater in range than with ordinary street-railroad systems, but also to afford insurance against interruption of traffic due to minor breakdowns in power stations and transmission lines. The New York Central in its desire to secure reliability has provided not only storage-batteries, but also duplicate power stations with access for fuel by both rail and water, either of which can, in the event of the disablement of the other, run the entire system, by utilizing spare units and working overload. Duplicate transmission lines have been adopted for like reasons. Since the commencement of electrical service last December, events have already proved the wisdom of these precautions.

The answer to this contention—that trunk-line railroads should use well-tried systems—is that no progress can be made unless something new is tried. In reply it may be stated that the trunk-line railroad is not the place to make experiments, but that interurban roads of minor consequence should be selected and the new system well proved before it is installed on a large scale in territory where its failure may have disastrous results.

Further commenting on the necessity for a study of local conditions, I have recently had in my charge the adoption of an electric system for operating combined freight and passenger service through a double-track tunnel now under construction. In view of the claims made by the advocates of different systems, it seemed wise to prepare the specifications so as not to cramp or restrict the judgment of the competitors, but leave the widest latitude for ingenuity and exercise of skill consistent with the accomplishing of the desired object. The invitation to domestic and foreign companies, in addition to asking for bids, also requested the filling in of blanks to show the annual costs, including interest charges, depreciation, taxes, and operation. The result showed conclusively that for that particular installation, the direct-current system was the cheapest in both first cost and annual cost, to the extent of from 20 to 25 per cent. less than its nearest competitor.

With your permission I would like also to give another illustration of the lack of wisdom in making broad generalizations from which to draw specific conclusions. We are often told that the overhead single-phase system should be used because of the advantage of requiring no sub-stations and sub-station attendance, but nothing at the same time is said about the higher cost of alternating-current locomotives for performing the same service, nor the higher cost of overhead construction as compared with the third-rail. About a year ago a pamphlet emanating from an eminent authority stated that on four-track trunk-line territory overhead construction would cost about $16,000 per mile, when as a matter of fact a recent actual installation has cost over $50,000 per mile! Also in a recent installation, while the first cost of the adopted system is somewhat less than one of the rival systems, still the increased consumption of current on one portion of the territory, capitalized, amounts to a very large sum. This amount added to the cost of installation, makes the equivalent cost considerably in excess of its rival. I am merely mentioning these instances as showing the necessity for fairly setting forth all sides of a problem before drawing a conclusion that may be entirely wrong; in fact I do not know of any important question of the day that so much requires absolute openness and frankness, with a careful examination of all sides of the case, as the adapting of electricity to trunk-line practice. Any concealment of the facts reacts sooner or later to the detriment of those responsible therefore and to the financial embarrassment of the suffering company.

I cannot too strongly endorse Mr. Sprague's remarks bearing on the wisdom of adopting the multiple-unit system for handling suburban service. The New York Central has already reaped its reward in adopting this method, in the elimination of practically all of the delays of train service at the Grand Central Station, delays that heretofore largely resulted from the multiplicity of movements of steam locomotives in passing to and from the engine-house facilities and in switching from the head to the rear end of trains; in fact, apart from other improvements made at this terminal, the use of the multiple-unit system has at this time resulted in an increase in the capacity of the station of at least 33 per cent. Moreover, the rapid acceleration of this character of equipment as compared with locomotive practice has resulted in the ability of the operating department to maintain schedules with a reduced rate of speed between stations. While on this subject of acceleration it might be well to add that in making a selection between the rival electric systems, relative acceleration should be compared not only in connection with the movement of suburban trains but also through trains hauled by electric locomotives. Some recent observations have demonstrated to me the marked difference of acceleration between the two principal electric systems. In changing motive power from steam to electricity on trunk-line railroads, this question of acceleration is one of the greatest attractions; it should, therefore, not be lost sight of in deciding upon any electric system which may offer no greater advantages in that regard than the steam locomotive that it displaces.

Another point mentioned by Mr. Sprague that seems worthy of special notice, is bonding of track rails. The New York Central has realized the wisdom of its course in adopting bonds concealed beneath the fish-plates, as there has been no loss from their theft; whereas I believe that on other roads where this precaution has not been taken, electrical operation has been seriously interfered with by the theft of exposed bonds.

In thus venturing a word of advice for closer relations between the steam railroad engineer and the electrical engineer, and greater frankness and cool reason in the discussion of the relative merits of the various electric systems, I may be pardoned a word to the electrical manufacturers in doing their part to popularize with steam railroad men the use of electricity in solving trunk-line problems. Always having in mind the primal elements of safety and reliability, all inventive genius of the great manufacturing corporations in this country should be bent on devising means of accomplishing a desired result at less cost, as this will mean in the end such an increase in the use of electricity as a motive power as to more than compensate for the comparatively small loss in decreased unit prices of apparatus. One of the promising movements in this direction is the hints that have been given of the possibility of substituting for the expensive synchronous converters and sub-station attendance of the direct-current system, a very simple device which will cost very little and require no attendance. This one feature, if successful, will go far toward strengthening the hand of the steam railroad enthusiast in extending the use of electricity more generally than now seems possible. The signal field is also one in which there is room for improvement in reducing costs of installation so as to make the use of electricity feasible from a financial standpoint. The use of electricity at the present day requires the throwing away of old type signals and interlocking systems and the installation of an entirely new system at a vast cost, due to the necessity for the use of the track rails for return propulsion current. On one of the branch lines of the company with which I am connected the substitution of electricity for steam has been indefinitely postponed because of the attendant greater cost of making a change in the block signals and interlocking apparatus; but I am pleased to say that one of the electrical companies now gives ground for hopes that a new method has been devised which will do away with the necessity for the more expensive portions of the apparatus and so far reduce the cost of the change of signaling as to make feasible the electrification of the branch road. It has seemed wise to give these illustrations as having a bearing on the rapidity of the process of evolution of change of motive power on trunk-line railroads.

As to the relative merits of overhead and third-rail working conductors, steam-railroad men have been more or less alarmed at the freedom with which contending enthusiasts argue as to the danger attendant upon the selection of either. It must be conceded that in return for the many advantages that come with the use of electricity, there are certain disadvantages; among these is the added danger from the use of working conductors, whether third-rail or overhead. The question simply simmers down to the selection of the system which appears to offer the least danger. Mr. Sprague has exhaustively covered the merits and demerits of each, and it remains for the steam railroad man to make a selection, having in mind the desiderata of non-interference with the view of signals, elasticity in the adjustment of tracks to new grades and alinement and the laying of additional tracks, minimum danger from derailments, safety to employes, and economy of maintenance.

I realize that my remarks on Mr. Sprague's exhaustive paper are very general and throw very little specific light on the problems that he discusses, but I feel that I might be pardoned for dwelling on a few of the features that have seemed wise for all of us to bear in mind in attempting to work together in bringing about as rapidly as possible the substitution of electricity for steam in places where progress demands increased capacity and the abolition of many drawbacks that necessarily accompany the use of the steam locomotive.

Lewis B. Stillwell: The Institute is to be felicitated upon the presentation of a long and interesting paper by a member who in the past has contributed largely, perhaps more largely than any other living man, to the utilization of electricity for traction purposes. With much, perhaps all, that this paper states in its first dozen or fifteen pages I am sure that we will find our opinions in agreement. We have noted a tendency of some electrical engineers to indulge in prophecy; the fact that some of us have difficulty in discussing railroad finance and operation unless we confine ourselves to glittering generalities has been frequently observed; that the hope of financial profit is the underlying motive which induces the capitalist to undertake electrical enterprises is a part of our engineering creed.

It is sometimes asserted also that an unfortunate tendency and limitation of engineers, as a class, is to concentrate their attention too closely upon certain features of a general problem and to lose sight of other features essential to a comprehensive and accurate mental prospective. Realizing this, it is satisfactory to note that the preliminary pages of the paper this evening aim to assist members of the Institute by suggesting a broad view of the general problem of electric trunk-line operation. It is distinctly disappointing, however, that, after casting his eye over the broad prospect which now appears to offer so inviting a field for the realization of increased earnings and decreased operating expenses by gradual, well-considered, and systematic extensions of electrification, the author should spend so much time and effort examining details of construction of assumed alternating-current and direct-current car equipments that he is able to bestow but a passing glance upon the sub-stations required for direct-current operation, and but hastily to examine the contrasted systems of transmitting power from coal pile to moving train. Herein the paper entirely fails to convey an accurate idea of their relative advantages and limitations.

In the paper of the evening, as also in his interesting contribution to the discussion of the paper which Mr. Henry St. Clair Putnam and I had the honor to present at the meeting of January 25, the author takes issue with certain opinions which I have expressed relatively to the question of standardization of electric railway equipment and the relative merits of direct-current and alternating-current motors for trunk-line operation. In the paper before us he says:

> But above the discordant notes, and in the turmoil of varied developments there rises now and then the cry of standardization, not only such as is natural and not prohibitive of new advances in the art, but wholesale explicit, and exclusive. For example, in a recent paper before this Institute, the view was expressed that but a single plan—the high-tension overhead trolley, with 15 cycle, single-phase alternating-current motors —was possible of serious consideration on trunk-line service, and that this system should now be adopted and standardized, despite the fact that there was not in existence a single equipment of this character in practical railway operation!

It is obvious that Mr. Putnam and myself failed to convey to the author of this evening's paper an accurate understanding of our position, and lest others also may have misunderstood our meaning I may be permitted to quote from the paper and its discussion the following paragraphs relative to "Standardization":

> Engineers constituting the membership of this Institute owe it to themselves, as well as to their clients, to use every effort, without prejudice and without fad, to prevent waste by opposing the introduction of apparatus which from its limitations cannot solve the general problem of railway electrification; and it is to be hoped that they will use their united influence to fix proper standards as rapidly as this establishment may be consistent with progress. * * *
>
> The necessity of proper standardization is obvious. Specifically it would seem feasible and eminently wise to agree upon standards of practice in respect to the following:
>
> (a) Location of third-rail.
>
> (b) Location of overhead conductor used with single-phase alternating-current-system.
>
> (c) Frequency of alternating-current traction systems.
>
> It is equally desirable but probably less easy to agree upon a standard system of multiple-unit control for train operation. * * *
>
> The position which we take in this matter may be stated as follows:
>
> a. A general view of the railway field, including freight as well as passenger traffic, obviously shows that for anything approximating a general solution the single-phase alternating-current system is decidedly superior to the 1200- or 1500-volt direct-current system. This conclusion is corroborated by calculations easily made and based only upon established facts.
>
> b. The admitted advantages of electricity in respect to increased earning power and decreased cost of operation are such as assure in the near future rapid increase in the use of electricity by railway systems now operated by steam.
>
> c. The necessity of standardizing frequency rests practically, although less directly, upon the same arguments as have induced railways to standardize track-gauge, train-line, and steam-line.
>
> In other words, the significance of our estimates of comparative operating costs is that the results, viewed in connection with admitted facts in respect to increased earnings, indicate that a general electrification of important railway divisions, and even of trunk lines, is coming much more rapidly than has been generally realized, even by electrical engineers; and the lesson to be drawn from this conclusion is that we must standardize as promptly as possible everything essential to convenient interchange of rolling stock.

Mr. Putnam and I have said nothing which excludes from further consideration the three-phase alternating-current system or any other alternating-current system, neither have we opposed the use of direct-current motors at any voltage in any kind of service, except trunk-line service in which it is proposed to substitute the electric motor for the steam locomotive. The line which divides trunk-line service from interurban service, of the class to which hitherto electricity has been applied, is sufficiently distinct, in most cases, to be recognized without difficulty. For interurban service I have used, and may continue to use for some time to come, direct-current equipment. Every real improvement in electric equipment adapted to rolling stock, whether that equipment be of the direct-current type or the alternating-current type, has its value. Each specific case of proposed installation obviously calls for careful comparison of available and adequate systems. Such comparisons, however, if they are to lead to conclusions that shall stand the test of time, must take into account not only existing and available equipment, but must recognize also tendencies in the development of the art, and consider probabilities of future extensions and possible connections of the specific line under consideration.

For trunk-line operation I have held and still hold the opinion that the 15-cycle, alternating-current, single-phase system possesses, inherent characteristics which, in this class of work, constitute controlling advantages as compared with any direct-current system that has been suggested, or is liable to be developed into an operative system. With this opinion the paper of this evening joins issue. In the oral discussion of the paper of January 25, the author of this evening's paper stated his position with emphasis by saying:

> I am going to make a prophecy, that on a large number of lines which can by any stretch of imagination be considered as subject to a reasonable prospect of electrification, 1200 or 1500 volts will on any present development known, give better results in every way than the alternating-current, 15- or 25-cycle overhead system.

The paper before us while presenting certain data and opinions purporting to sustain the contention that the 1200-volt direct-current system is superior to the 15-cycle alternating-current system, presents no sufficient and fairly comparable data upon which any such conclusions can be based. The only data which it presents in the way of a comparison of the relative outputs, speeds, and weights of the contrasted types of motor are those in which a direct-current motor rated at 240 h.p. and an alternating-current, 25-cycle motor rated at 125 h.p. are compared. A pyramid cannot be made to stand long upon its apex unless propped up, and no conclusions as broad and far-reaching as that which this paper apparently endeavors to establish can be based upon a single comparison of this kind. Even this single exhibit obviously requires material correction before it can be used properly as a premise for the conclusions which the author seeks to draw. It is defective for the following reasons:

1. It compares two motors of equal weight. This comparison used as a basis for a general conclusion is, obviously, unfair to the alternating-current motor, as it takes advantage of the fact that increase in the size of motors of any type, alternating current or direct current, implies reduction in weight per horse power. Had the comparison brought together two motors of equal output, the ratio of weights would have been far less than is the ratio of output when equal weights are considered. The particular case of a motor-car equipment in which it appears that four 25-cycle alternating-current motors would be required to do the work of two 550-volt direct-current motors is one which has come up in my own experience, but, obviously, it is no proof that similar relations would hold, for example, in equipping a locomotive with a given aggregate horse power.

2. The comparison is made with a 550-volt, direct-current motor weighing without gear, gear-case, and pinion, only 23 lb. per h.p. (one-hour rating). This is extraordinary light and indicates that the motor is, in respect to the relation of weight to output, superior to anything in general use. The latest 200-h.p. motors offered within the last 60 days to the Interborough Company by our leading manufacturers weigh, respectively, 28 and 30 lb. per h.p. (one-hour rating). The alternating-current motor in Mr. Sprague's comparison, on the other hand, is characterized by a higher relation of weight to output than other single-phase motors of comparable output in the market.

3. The comparison is between a direct-current and an alternating-current motor operating at 25-cycles, not 15-cycles, which is the frequency suggested by Mr. Putnam and myself. The 25-cycle single-phase motor has a far higher ratio of weight to output than the 15-cycle motor of the same output.

The paper emphasizes the statement that "Capacity is the keynote of equipment." With this conclusion few will differ. In our consideration of capacity of equipment, however, we should not limit our attention to the motor but should take into consideration, also, the comparative methods of transmitting power to the moving trains. In general, the choice of a system will depend upon the ratio of capacity as measured in tractive effort to aggregate cost of equipment.

I have read the paper of the evening somewhat hastily and possibly may have overlooked an adequate statement of the advantages of the alternating-current systems which result from the elimination of the converter substations. These, as is well recognized, are a very expensive element of the direct-current system as it would be applied to anything resembling a trunk line—expensive not only in first cost but relatively still more so in annual cost and in complication of the distributing system. There are to-day in operation in this city somewhat over eighty 1500-kw. converter units for the purchase and installation of which I have accepted responsibility. While this machinery is doing excellent service, I know enough of its cost and limitations to realize that for trunk-line railroad operation in the broad sense a system which employs the converter as an essential link between the coal pile and the train must give way to a system which eliminates this link, provided the single-phase, alternating-current motor is designed and manufactured with anything approximating the care which to-day is bestowed upon the direct-current motor.

As I have said, a pyramid should not rest upon its apex; general conclusions, too, in respect to the very important question under consideration, should not be based upon comparison of a single representative motor of each size. Such comparison should rest upon comparative data prepared by competent designing engineers, working without prejudice in favor of one system or the other, and should comprise essential facts covering a considerable number of motors of various output, designed for the same service. It is to be hoped that some of the designing engineers of our manufacturing companies will prepare and present such data in connection with the discussion of this paper.

Meantime, however, I may say that only last week with reference to a specific installation which I am studying, I obtained from the engineers of one of our large manufacturing companies comparative figures relating to 15-cycle, single-phase, alternating-current motors of 200 h.p. at one-hour rating, and 600-volt, direct-current motors of the same output. These motors are practically identical in speed when delivering 200 h.p. The data in which I was particularly interested are the maximum vertical dimensions and the weights of these motors. The maximum vertical dimension of the alternating-current motor is 36.5 in.; that of the direct-current motor is 1.625 in. less. The weight of the alternating-current motor is 6280 lb.; that of the direct-current motor is 6000 lb.: both of these weights are exclusive of gear-case and pinion. The alternating-current motor requires a wheel-base one foot longer than is necessary with the direct-current motor. The ratings in the case of both motors are based upon the same rise of temperature without forced ventilation.

I am not sure that I understand the author's reference to the implied necessity of increasing the current-carrying capacity of steel conductors. He quotes from the report of the commission of the recent International Electrical Congress to show that on 80-lb. rails the ratio of impedance to resistance at 25-cycles is about 9 to 1. This difference is, of course, well known; but in transmitting a given amount of power by single-phase alternating current through overhead trolley and track return at 11000 volts, even when a frequency as high as 25 cycles is employed, the reduction in current implied by the increased voltage makes the total drop in the circuit, as measured in percentage of applied potential, less than $\frac{1}{10}$ the drop of a direct-current system operating through the same circuit at 1200 volts.

It should be noted carefully that while the only comparative data given with respect to motor performance relate to the 550-volt, direct-current motor, the paper implies that in competition with the alternating-current system a direct-current potential of 1200 volts will be used. It is for our designing engineers to supply adequate data, but I venture to express the opinion that comparing the 15-cycle, single-phase, alternating-current motor with the 1200-volt, direct-current motor, the latter will, in general, have very little, if any, advantage in respect to dimensions or weight. Moreover, it is not to be lightly assumed that synchronous converters delivering 1200 volts would be found as cheap and as reliable as the 600-volt machines now in use.

When we come to consider the auxiliary car equipment and wiring there is a very radical difference in favor of the alternating-current system. In this field as in the lighting field the transformer is the key to the solution of the general problem of transmitting energy at reasonable cost and utilizing it at safe and easily controlled potentials.

W. B. Potter: Using the word system in the sense of meaning the different modifications of direct and alternating current, I think all will agree that the state of the art is not such as to warrant the recommendation of any particular system as the standard and the only standard for future consideration. With reference to existing installations, the 600-volt, direct-current system and apparatus is certainly a recognized standard, which is more than can be said of the apparatus on any of the other installations, at least in this country. In nearly every case where a choice between systems is considered, there are controlling conditions with respect to financial advantages or local requirements which are of sufficient prominence to determine the particular system most suitable for the case under consideration. The proper attitude of the engineer toward commercial undertakings, with which most of us have to deal, should be that of an investor, his reputation being his capital and his dividends being in direct proportion to the economic success of the work for which he is responsible. I feel that Mr. Wilgus has well expressed this sentiment in saying that an important trunk-line railroad is not the place for experimental development, but that such work should be done on branch lines where failure or partial success would inconvenience a smaller number of persons. To a large degree new types of apparatus can be perfected by manufacturing companies, by experimental operation on suitable tracks; but in the actual operation of apparatus conditions invariably arise that do not develop under the control of the designers and which can only be eliminated by such advisable modifications in design as become apparent from a careful study of the apparatus in service.

For a number of years the improvement in direct-current apparatus has been principally with respect to its mechanical features. Within the last few years, by the application of commutating poles, there has been a decided improvement in commutation, particularly with direct-current railway motors. These motors, by reason of physical limitations and the fixed position of brushes necessary for operation in both directions, are particularly difficult to design electrically. From present indications it would appear that for other than bi-polar motors the recognized standard direct-current railway motor will undoubtedly be provided with commutating poles. Granting a motor of suitable capacity, the character of the commutation is of the utmost importance to the operator, since defective commutation means decreased reliability, increased cost of maintenance, and a degree of supervision out of all proportion to the other parts of the motor.

This problem of commutation, which has been so effectively solved in the case of the direct-current motor, is one of the principal difficulties to be overcome in the single-phase, alternating-current motor. The commutation of this is inherently inferior. Another feature of the alternating-current motor incidentally affecting commutation is the number of armature revolutions relatively to the car-speed; the armature speed is somewhat higher than that of the direct-current motor. The higher speed of the armature is not necessarily a feature of single-phase motor design, but owing to the comparatively greater weight of this motor it is desirable to run the armature at as high a speed as is consistent with satisfactory operation of the bearings.

The single-phase motor is a comparatively recent development. We have good reason to expect substantial improvements in its design, particularly with respect to commutation; and I am pleased to say this evening that the prospects are particularly encouraging for a single-phase motor with commutation as good if not better than that of direct-current railway motors without commutating poles, and with an armature speed only slightly higher than that of the direct-current motor. As this improvement in commutation is got without the use of resistance leads, the internal losses incident to such leads, or the losses due to local current in the armature, are largely avoided and the efficiency of the motor is improved. The weight of such a motor will still be probably about 25% greater than that of a direct-current motor of the same rated capacity.

These improvements do not affect the application of the different systems, except that they may result in reducing the cost and maintenance of the single-phase apparatus. They do, however, raise the quality of the apparatus more nearly to that used in present direct-current practice.

The 1200-volt direct-current system, to which special reference has been made by Mr. Sprague, is substantially in line with present-day practice for 600-volt apparatus. The commutation gives every evidence of being as good as with 600-volt motors, the only provisions necessary being additional insulation both with respect to the coils and creepage distances on exposed surfaces. With respect to the higher voltage direct current, I would suggest that 1200 volts be accepted as the next higher standard above 600 volts. The use of a number of intermediate voltages would introduce a variety of apparatus not suitable for general use, and necessarily more expensive, as it would be manufactured in limited quantities only. On account of the practical relation of speeds easily obtained with the series-parallel combination of the motors, 1200 volts afford better opportunity for interchangeable operation with 600 volts than with any intermediate voltage.

As an illustration of the attitude of operating companies concerned in getting apparatus most suitable for their service, I would mention that at the present time there are being manufactured for use in this country, railway apparatus for 600- and 1200-volt, direct-current systems, a 6000-volt, three-phase system, and a number of 25-cycle, single-phase systems of different voltages.

Charles F. Scott: The author makes comparisons between direct-current and single-phase, alternating-current apparatus. I have been particularly interested to detect his method in arriving at conclusions which are so largely at variance with those of some other engineers.

First of all he lays stress upon the relative capacity of the motors of the two types as being one of the important and controlling elements in reaching a decision. He takes certain data and a certain basis of comparison, and from these reaches apparently logical conclusions. The question then arises, are the data and the basis of comparison correct? If not, are there not other data and another basis of comparison from which conclusions may be drawn by the same method, but perhaps with different results?

It seems to me that a number of points which Mr. Sprague has taken up are comparisons on a particular basis, and that he has not considered fully the different methods or conditions under which the two motors may operate; for example, in comparing the curves of the two motors, he shows that the alternating-current motor has at light load a much higher speed than the direct-current motor under the conditions which he has taken. There is an apparent conclusion, therefore, that the alternating-current motor is lacking in the excellent characteristics possessed by the direct-current motor. He has failed, however, to call attention to another point; that is, the ready adjustability of voltage in the alternating-current system by means of voltage taps from the transformer. By this means the motor, instead of operating to its highest speed under a single applied voltage, which is the usual condition with the direct-current motor, may have a lower voltage applied. It may, therefore, develop different torques at different speeds, depending on the controller position. Under the control, therefore, of the motorman, the alternating-current motor is not limited to a single law of acceleration, but may have different rates of acceleration, adjustable as desired; it may, for example, have the same mean acceleration from start to maximum speed as that of a direct-current motor, but with a less maximum rate of acceleration.

Another point in which changed conditions were not taken into consideration is that of rail-loss. Although the loss per ampere may be greater, the loss per kilowatt may, as pointed out by Mr. Stillwell, be much less.

It appears that the author, in his treatment of the subject has, unconsciously perhaps, assumed the direct-current motor and its characteristics as the ideal of perfection, so that wherever the other motor has different characteristics, these characteristics were naturally and *per se* objectionable. At any rate, he has apparently not recognized or emphasized certain advantages on the side of the alternating-current motor, In certain cases the voltage control can give a higher speed than normal to a motor in service. The application of higher voltage gives not only higher speed, but greater output as well. Something of the same nature is attained by field-control in the direct-current motor, but the field-control is a method of adjusting speed without increasing the capacity of the motor. The same voltage is applied, and the permissible current through the motor remains the same, and hence its capacity is not increased. But with the alternating-current motor an increased voltage is applied to the motor which gives an increased output, with the same current going through its armature. The paper, furthermore, gives but little consideration to the advantages inherent in the alternating-current system between the power house and the train, through the elimination of synchronous converters and the reduced current to be carried. The rheostatic losses in direct-current equipments, a matter which in some kinds of service is of considerable importance, has not been touched upon.

The matter of electrical braking has been referred to. A paper on braking with single-phase motors is to be presented at the next Convention by Mr. William Cooper. The paper will deal with a method which has been worked out and fully tested, whereby it is found that the single-phase motor lends itself admirably to braking, covering, as I recall, all the desirable qualities in braking which have been called for by the author and doing far more than has been shown possible with the direct-current motor.

N. W. Storer: The question of third rail versus overhead construction for electric railways is a matter concerning which it is unnecessary to theorize, because, with the large systems now in operation or about to be put in operation, it will very soon be settled by experience.

I desire to take issue with the author in regard to some statements concerning single-phase equipment, as information that I have is entirely at variance with what appears in the paper. In the first place, there are given fifteen so-called differences between direct-current motors and alternating-current, single-phase motors. These might have been called, "The advantages of direct-current motors as compared with single-phase motors," as this is what they are made to appear. Although many of these are of little consequence they will nevertheless be considered in order.

1. "The input of current in one is continuous; in the other, intermittent." Quite true, but the draw-bar pull is quite as effective in one case as in the other

2. The direct-current motor has a solid frame like the single-phase motor It has, further, two or more laminated poles bolted in, and if the interpole construction is used has as many more relatively small and delicate poles. The alternating-current motor as built by the company with which I am connected has, in all sizes up to a diameter of 38 in. field punchings made in a single piece and built up and keyed in the frame,

making it as solid a construction as an armature on its spider. The claim for less rigidity in the single-phase motor is, therefore, not sustained.

3. " One has exposed and hence freely ventilated field-coils; the other has field-coils embedded in the field-magnets." It is known to most motor designers that coils in contact with iron will dissipate heat much faster than when in the open air. This is especially true of coils in an enclosed motor. I have repeatedly noticed that motor field-coils which have been removed on account of roasting, have shown the insulation in contact with the pole pieces to be in good condition, while other sides were badly roasted. I know, therefore, that in respect to ventilation of field-coils, the single-phase motor is superior to the direct-current motor. Smaller cross-section of coils also allows the heat to be radiated better in single-phase motors, and the fact that a large part of the loss in the motor is concentrated in the field iron will enable the motor to dissipate a much larger amount of heat for a given temperature-rise than will a direct-current motor.

4. Concerning "polar clearances." Many thousands of direct-current motors are to-day in operation with a clearance of $\frac{1}{8}$ in. to $\frac{3}{16}$ in. between poles and armatures, and in practically all cases where more than $\frac{3}{16}$ in. clearance is used it is for electrical reasons. Further, while the smaller air-gap used for single-phase motors was at first much feared, the fears have proved to be without foundation and the present clearances of from 0.1 in. to 0.15 in. have proved to be ample and fully as good as 0.15 in. to 0.25 in. in direct-current motors, because there is no unbalanced magnetic pull.

5. Concerning "torque." The torque of an armature is the pull it will exert at one-foot radius. Therefore it makes no difference in the result whether it is obtained with large flux and few armature conductors, or vice versa.

6. " A much larger diameter of armature and commutator, and runs at a much higher speed." This is a very general statement: what are the facts? The armature diameters ordinarily run from 5 to 15% larger than for direct-current motors of corresponding output. It is undoubtedly true that the armature speeds of the earlier single-phase motors were much higher than the speeds of corresponding direct-current motors; at the present time, however, the speed at the nominal rating of the motor is practically the same as that of direct-current motors, and the maximum operating armature speeds are within the safe limits set for direct-current motors.

7. Concerning " gear-reduction and gear-pitch." The gear-reduction depends, of course, upon the speed; and as far as gear-pitch is concerned, I wish to say that the same gear-pitch is used for single-phase motors as for direct-current motors of the same capacity.

8. " The windings of one are subject to electrical strains of

one character; in those of the other the strains are of rapidly variable and alternating character." No conclusion is drawn from this. It may be of interest to know that there have been a number of instances where the single-phase motor has broken down in service on a direct-current section of the line, necessitating cutting it out of the circuit; but when the car reached the alternating-current section of the line it has been again connected in circuit and operated satisfactorily, thus indicating that the electrical strains with alternating current are less severe than with direct current.

9 and 10. Concerning the "variable torque of the single-phase motor." No comment is made as to the relative merits of uniform or pulsating torque. In a recent discussion before the Institute, Mr. Potter called attention to certain characteristics of the torque exerted by an alternating-current motor, especially when it reaches the slipping point of the wheels. It was stated that there is an apparent advantage in the pulsating torque, because, when the motor starts to slip it does not immediately decrease its mean torque, as is done in the case of the direct-current motor, but slips in a series of jerks apparently regaining the hold on the rail at every pulsation.

11. Concerning the "number of poles." The paper states that the direct-current motor has "two or four main poles only." No direct-current motors built in the last 15 years except those on the New York Central locomotives have less than four poles. The paper states that the alternating-current motor has "eight to fourteen poles." The single-phase motors built by the company with which I am connected have four poles for all sizes up to and including 125 h.p. The largest single-phase motor thus far built has a capacity of 500 h.p. It has but 12 poles.

12. Concerning "a high torque while standing still." As we understand the matter, railway motors are designed to move a train rather than to hold it at rest. At the same time we know that the single-phase motor is amply protected against mistakes of motormen in leaving the current on the motor for a half-minute or so with brakes set.

13. Concerning "resistance in commutator leads." It is well known that the resistance leads used in single-phase amatures are for the purpose of reducing to a minimum the loss due to the transformer action in the short-circuited coil. Their presence is fully justified and the efficiency is higher than it would be if they were not used.

14. This refers to relative weights concerning which I shall have something to say farther on.

15. On this point I agree absolutely with the author. There is one type of construction to which the single-phase motor is not adapted. This is so far employed in only a single case.

More or less is said in the paper concerning the lower efficiency of the single-phase motor, and inference might be drawn that it is about 10% lower than that of the corresponding direct-current motor. Just to show what modern motors are capable of doing, I give below in parallel columns the efficiencies of corresponding sizes of direct- and alternating-current motors at different percentages of their full-load torque.

Per cent. of full-load torque	Direct-current 90 h.p. motor	Alternating current 25-cycle, 100 h.p motor	Direct-current 200 h.p. motor	Alternating current 15-cycle, 200h.p motor
125	86.25	82.	88.8	87.3
100	86.8	85.	89.	88.
80	87.	86.	89.2	88.3
60	86.5	86.8	88.8	87.7
40	85.	86.	87.	85.
25	82.	82.5	84.	82.

From this it does not appear, within the ordinary range of tractive efforts exerted by railway motors, that the single-phase motor is so far deficient. In fact, it comes remarkably close to that of the direct-current motor.

Concerning the comparison between the 125-h.p. and the so-called 240-h.p. motor contained in the paper, I take issue, with the author. In my opinion the only reasonable way to compare the performance of single-phase motors with that of direct-current motors is to assume a car with a certain seating capacity, and then consider what equipment, alternating current or direct current, is suitable for this service. It is not fair to assume, as is done in the book by Messrs. Parshall and Hobart, a car of a certain total weight, carrying in one case fewer passengers than in the other. The object of a railway company is to accommodate a given traffic. It follows, therefore, that an equipment should be provided which will be serviceable. Motors should be selected on the basis of their speed-time curves and in accordance with their particular characteristics, rather than upon the simple horse-power basis. Further, it is unfair to take an isolated case of a single-phase motor which may be heavier than the ordinary and compare it with a direct-current motor which is certainly much lighter than ordinary motors of that capacity. If, in seeking to compare the two types of motors, the author had taken the 25-cycle, 75-h.p., single-phase motor referred to later on in the paper his conclusions might have been quite different. The weight which he assigns is 4199 lb. The weight of the corresponding direct-current motor is 3500 to 4200 lb. Moreover, if the single-phase motor to which he refers were operated on 15 cycles instead of 25, its output would be 90 to 95 h.p., which would lead to conclusions quite at variance with others in the paper. The weight of a quadruple equipment of

90-h.p. direct-current motors furnished by the company with which I am connected would be approximately 20,000 lb. The corresponding weight of a quadruple equipment of 90 h.p., 15-cycle motors with oil-insulated transformers equipped for 11,000 volts would be approximately 27,500 lb., an increase of about 37.5%. This extra weight added to a 40-ton car would amount to about 10%. Owing to the greater efficiency in controlling single-phase motors, the power consumption of the car, including transformers, would in most classes of service be approximately the same as that of the direct-current motor at the trolley and would be much less at the power house. I wish to say, further, that a car for passenger service can be equipped with two 200-h.p., 15-cycle, single-phase motors giving ample clearance on 37-in. wheels, and that these two motors will operate a car with the same power consumption per car-mile at the car on runs as long as five or six miles as would be obtained with a car of the same capacity operated with an equipment of 200-h.p., direct-current motors. On shorter runs the relative power consumption would be less.

Now, concerning the use of high-voltage direct current. Motors can certainly be built to commutate satisfactorily on 1200 volts direct current. Such motors, however, must restrict the voltage between bars to a safe limit, and have extra space for insulation. The construction of this motor would therefore put it on a par with the 15-cycle, single-phase motor both in weight and dimensions. Moreover, it would have practically the same air-gap in moderate sizes of motors, and might possibly have to be designed with the same style of compensating winding on the field as is now used for single-phase motors. It would have in addition the disadvantage of a high voltage always present on the windings and brush-holders. If it were not for the greater possibilities of the single-phase system, there is no doubt but that the high-voltage, direct-current motor would be quite attractive. As it is, I believe that systems should be developed which offer the best solution for the entire railway problem. To attempt to develop a number of systems would result in not only scattering the energies of manfuacturing companies, but would retard the ultimate solution and supply the railways with a heterogeneous collection of equipments that would postpone standardization for many years.

G. R. Henderson: I am particularly pleased to find that the writer of the paper does not claim that electrification is a panacea for all railroad ills, but when applied to individual cases which have been intelligently studied and found to be suitable for such treatment, satisfactory results may be expected.

That success depends upon traffic density is made clear, and the importance of the load-factor is brought out, and I heartily agree with the assertion that trunk-line operation is vastly different from suburban service. As the two extremes, consider the New York subway, with constant trains at short intervals, and a division on a western road handling stock almost exclusively. There are one or two days a week when the stock must be brought to market, and perhaps from 12 to 20 trains will be run in one direction, possibly up-grade, at 15- or 30-minute intervals, as the market must be reached in time to avoid claims. Then for four or five days there may be nothing but one or two passenger trains and a local freight. Can any one imagine a railroad company rash enough even to think of electrifying its road in such a case? The power house and conductors would have to be proprotioned for the maximum traffic, but the average load-factor would not be ten per cent. Operating methods can no doubt be changed in many cases to advantage, in electric traction, but such traffic as I have referred to cannot be altered to suit transportation requirements.

The important factor of financial success is also brought out in the statement that unless a commensurate return on the increased investment can be assured, steam locomotives will not be abandoned. This item of first cost is an important one, when we consider that one horse power in steam locomotives costs about $10, and in power house, lines, etc., about $100. Electric locomotives themselves cost double the amount of steam locomotives, and as the average cost of coal in the Uinted States does not exceed $1.50 or $2 a ton, little may be obtained from fuel economy.

The great possibility of the electric locomotive in freight service (and this is usually the dividend-earning part of the traffic) seems to lie in the increased power available by small reductions in draw-bar pull corresponding to increase in speeds; but the relative value for each and every line can only be determined by making a careful study of all the factors involved for that particular piece of track. Comparisons with other roads may, therefore, be not only useless but positively dangerous, unless all the conditions are understood. These computations are laborious, but absolutely necessary. When we consider the different rates of pay and the cost of commodities in various parts of the country, and the effect of physcial conditions of the track, we realize the importance of careful analyses. By varying the train load we can run the cost of transportation per ton-mile to double the minimum figure, the charges for material and labor remaining constant, which shows how complicated will be the deductions from a thorough investigation of the subject, but unless so made they may be worthless. Characteristic power curves of both steam and electric locomotives would naturally form the basis for such a comparison, and these should be carefully laid out; and then by making combinations of diagrams representing the locomotive power and train resistance, the important fundamental advantages can be deduced for a variety of conditions.

According to the writer, regeneration is not promising as a method of reducing power consumption any more for electric than for steam traction, but it may reduce brake-shoe wear and lengthen the life of wheels. It could not replace the air-brake, however, for obvious reasons, but might be compared in its action to the Le Chatelier or Sweeney brake. Even air-brakes are now arranged so that they can be held upon the locomotive while re-charging the train on long grades, and retarded release is provided so that the rear-end brakes let go first.

I am glad to see that multiple-unit control is not considered feasible for freight operation, and that the great difference between this and suburban transportation is made clear. We heartily agree that it would not be wise to attempt to handle heavy trains on steep grades with one man, and the legislators would no doubt prevent it. The presence of a third man on locomotives of the Wooten type has often been discussed by our lawmakers, and the single man and multiple-unit control would certainly excite much opposition.

Having had twenty-five years' practical experience on railroads from the Atlantic to the Pacific, some of them operating on 3.5% grades over the Rocky Mountains, I cannot too heartily express my approval and endorsement of the very conservative statements and the sound logic enunciated in this paper; I believe that if these points are constantly kept in mind there will be few electrifications to criticise unfavorably, and that those who decide to abandon the steam locomotive will be able so to fortify their position with convincing figures and data that financiers will provide the funds and the results will justify the expenditures necessary for the work. While I do not expect to see the steam locomotive driven "off the earth", and am confident that for many years it will still be found performing most of the work of transportation in this country, yet I do believe that the electric locomotive is bound to increase rapidly in number and in favor, and that each in its own proper sphere, steam and electric traction, will coöperate to the advancement of transportation and the increase of prosperity.

William McClellan: It is to be regretted that the author has thought it wise to spend so much time comparing motors when it is well known that the single-phase motor is not equal in weight-coefficient or efficiency to the direct-current motor. From a practical standpoint the comparison should be made on the complete system from the coal-pile to the transported load. My experience in making comparisons of the several systems for different roads confirms the figures stated by those who have discussed the paper rather than the figures of the author. After operating an 11,000-volt, multiple-unit train under extreme weather conditions and heavy overload, it is a pleasure to report that the equipment is extremely flexible in every way and gives remarkably smooth operation. The control of motor voltages by the transformer taps seems to make for very smooth acceleration. The examination of the commutators with covers off showed, under heavy overload, sparkless or black commutation.

Even when one of the cars was acting more as a locomotive than as a motor-car this was true. In these circumstances it is particularly gratifying to-night to learn that even better conditions can be expected from equipments produced now.

The author's paper spells the word "capacity." First, capacity of the truck for motors; secondly, capacity of the trackage for traffic. We certainly must all agree with the latter argument. There is little doubt that the electric motor can be introduced on steam railroads more easily by showing that the capacity of the ultimate trackage in a given locality can be increased more by electrifying than by any other motive power. It is probable that hundreds of miles of trunk-line electrification will be installed for this reason, before there will be sufficient information on the relative cost of operation and similar data.

It does not seem, however, that the capacity of the truck to receive sufficient motor power will ever be a serious menace to the success of the alternating-current motor, even if the present weight-coefficient is not improved. This objection obtains chiefly in connection with locomotive design. It should not be forgotten that almost all electrification so far has been in connection with terminal work where an electric locomotive must receive a train from a steam locomotive for a short run through a tunnel or otherwise. The more I study the problem, the more I am convinced that when we come to the electrification of a whole division, we shall depart from locomotive practice and turn to multiple-unit equipment. Even for through service it is more than likely that it will be found cheaper in the end, more elastic, and less liable to cause delays on the road. This has been forcibly impressed on me recently, while making some trial runs with new multiple-unit trains on a trunk-line division. Several times minor accidents happened which, had the motive power been concentrated in one unit, would have stalled the train for some time. With the multiple-unit train, however, it was very easy to cut out one car and make a run in without seriously disturbing the schedule.

Even in connection with freight traffic our present ideas may have to undergo a radical change. As we understand it now, receipts are per ton-mile while expenses are per train-mile. There is a possibility, however, that with electric operation we may be able yet to show that the quickest and least expensive method of getting freight over a given division is not always by means of the longest train and the heaviest locomotive.

In view of the fact that most of the engineers who are ardently expressing faith in the single-phase motor are at the same time advising the use of, and installing, 650-volt third-rail and overhead apparatus, it is a pity that there should be an opinion held that we are divided into hostile camps. Arguments comparing overhead construction with third-rail have been made so exhaustively and so frequently that there is little use here in repeating them. Since both are being introduced in various places we can afford to wait for time to bring out the truth.

There are reasons, however, why, for trunk-line operation, opinion seems to be so strongly in favor of the single-phase motor: first, it is generally acknowledged that on account of expense and complexity of power distribution a 650-volt, third-rail installation, no matter how well done, will never solve trunk-line electrification. It seems evident that the case demands a high voltage, which in turn necessitates an overhead structure. If the present single-phase motor is not adequate or satisfactory, it must be improved or another type designed. If the present type of catenary construction fails in service, it may have to undergo radical change. In spite of these details, of the highest importance as they are, the general statement in regard to the system remains true.

Secondly, the electrical engineer must follow the engineer-of-way. The former must electrify whatever system of trackage the latter demands for moving his traffic. In large terminals and busy yards, unless present methods of switching can be revolutionized, the third-rail is not always available. I do not know of any extensive proposition where the third-rail had been adequate in such cases. The paper itself, though slightingly, refers to one large terminal where considerable overhead structure had to be introduced. This adds undesirable complexity to the car and locomotive equipments. In this connection it must be remembered that locomotive shoes will probably not span a gap much greater than 25 ft. This fact introduces troubles not met with in connection with multiple-unit trains.

Thirdly, every large road is a problem which must be considered financially on its own merits, but technically in relation to the whole system and to other roads with which it may come in contact. That system of electrification which may be most suitable for the operation of a large terminal may be one which it is unwise for the road to adopt, because sooner or later this may have to be extended to the whole system. Neither can the largest roads afford to ignore absolutely what other roads are doing in the way of electrification. The modern trend of enterprise is towards consolidation, exchange, and pooling. There is in process of formation, or perhaps already finished, a freight-car pool among the larger roads of the country; it is not beyond possibility that ten years from now may see a pooling more or less complete of passenger cars; and there is no doubt that many parallel roads to-day could adopt joint track agreements to the advantage of both and the great advantage of their patrons. It is these possibilities that a road must keep in mind when it starts to electrify, or it may later have to expend enormous sums of money to bring itself into conformity with a larger system of which it may become a part. Therefore, reasonable standardization is one of the things we should have on our minds all the time. No question should be decided without considering this point of view.

A. H. Armstrong: It is very difficult for the writer to share the confidence expressed by some of the previous speakers as to the exact trend of future railroad engineering. This is an age of development. Things change over night and impressions formed last week are quite likely to stand in need of modification in the light of more recent developments. In this connection I may state that my impressions of alternating-current motor performance, which have been gradually forming as the result of several years' experience with such motors, have been very agreeably shaken by tests witnessed during the last few weeks.

I had an opportunity to witness a test on a 125-h.p. series compensated alternating-current motor operating at 50% overload. The commutation was excellent, as good as that of present direct-current motors, and was obtained by certain recent modifications in motor design and connections.

New developments are not confined to any one type of apparatus. The direct-current motor has exemplified this in the vast improvements made in the last year by the introduction of the so-called commutating-pole type of motor, which practically eliminates the question of commutation as a disturbing factor. Owing also to the development of the commutating pole, it is possible, with the better results obtained, to wind such motors for 1200 volts. The commutation of these 1200-volt motors is even better than the 600-volt motors hitherto used. It is, therefore, hard to predict with any certainty just exactly what field is covered by any one type of apparatus. We now have offered direct-current motors of 600 and 1200 volts that give practically perfect commutation, very high efficiency, and an adaptability of design that makes such motors applicable to a wide range of railway problems. We have also recent evidence that the alternating-current motor can be so improved as to approximate closely the present performance of the direct-current motor not having commutating poles. Such improvements must have considerable weight in determining the future field of application of this type of motor. I will say for the benefit of those that are anxious to standardize the frequency of 15 cycles, that the tests I have reference to were made at 25 cycles, and seemed to indicate that a thoroughly good alternating-current motor could be built without the necessity of adopting a new frequency with all the incidental complications involved in so doing.

Mr. Ferguson has expressed an opinion to the effect that the railway load in and around large cities like New York and Chicago represents only about 25% of the total electric power developed. in these territories. The use of 25 cycles is almost universal in and around large cities, and it would become a very serious commercial matter, owing to like conditions over all the country, if the future of the alternating-current, single-phase motor depended upon the adoption of a lower frequency.

I find myself repeating the advice given by Mr. Wilgus, to the effect that the electrification of our steam roads calls for cool, unprejudiced, common-sense engineering. Like him I believe that the cause is injured by too strong enthusiasm for any one type of apparatus, and the best showing can only be secured by considering the type of apparatus best suited for the particular needs of the road in question as determined after a very careful unbiased investigation of the local requirements.

C. P. Steinmetz: I wish to endorse the statement that we are not yet ready to standardize one type of railway motor, or one method of electrifying steam railways. We shall not be ready to do so for some time; perhaps never. I agree with Mr. Wilgus that each railway problem should be considered on its own merits. The proper method of solving the problem in hand should be to apply the standard that has been found satisfactory by extended experience, and not deviate therefrom except where it is absolutely necessary. As has already been said, the problem before us is to substitute electric motors for steam locomotives where the conditions of service have grown beyond the capacity of steam locomotives. Whether the alternating-current or the direct-current motor has the advantage is rather a secondary question; the main question should not be lost sight of in discussing conflicting claims for the one or the other type of motor. At present there is an alternating-current motor and a better direct-current motor, regardless of the contention that the alternating-current motor is equal to the direct-current motor; for at the same speed and same energy input there is saved in the direct-current motor the power lost in commutating, and that lost as hysteresis in the field. The heating is less, and consequently the efficiency is greater. Now since the mechanical output or capacity of the railway motor is controlled by the heating, the alternating-current motor on a direct-current circuit gives the same mechanical output at a lower temperature; with the same temperature it gives a larger output

There is a class of service where alternating-current motors are necessary—a long railway with infrequent and irregular service, and a considerable amount of fluctuating freight traffic—in short, conditions where synchronous converter sub-stations would show a poor load-factor. In such cases, direct-current operation appears impracticable, and here is the field for the alternating-current motor or the steam locomotive. Where there is a 4-track or a 6-track railway with traffic so heavy that the distance between trains is limited only by safe headway, the load on the converter sub-station is so nearly constant, the load-factor so great, the rapidity of acceleration required so considerable, and the maximum capacity of the motor so great that the advantage is decidely in favor of the direct-current motor. In such cases there is no excuse for using alternating-current motors.

I do not share the objections to the synchronous converter, and do not believe there is any gain in reliability in eliminating this link. It is an advantage in a system to eliminate some of the links, but what wants to be eliminated is the weakest link, and that is not the synchronous converter, but the motor. A synchronous converter is about the strongest link. However, between these two extremes there is a very wide field where either the alternating-current or the direct-current motor may be used, or rather where different engineers may be justified, impartially, in arriving at different conclusions; but what should be guarded against is the adoption of any one system which precludes one for ever from changing over to any other system. I refer specifically to the adoption of an arbitrary frequency. At present, after many years of work we have succeeded in eliminating all frequencies but the two now universally used—60 cycles and 25 cycles. At the present time all the heavy power of the country is transmitted at 25 cycles. Adhering to this standard frequency, it would not be so formidable a thing to use the alternating-current motor and then find that after all, the direct-current motor would be better. The alternating-current motor could be used for outlying side branches of a railroad and the main line be operated with direct-current; or, inversely, a start could be made with direct current and later changed to alternating current, provided the interchangeability of the system be not lost sight of. Herein lies the harm of radically changing the frequency. Compelling one to adopt a frequency of 15 cycles brings about a very serious condition; it means giving up the possibility of securing the benefit of interchangeability with the large amount of power now available at 25 cycles. In brief, 15-cycles would be an odd system, as odd as the 40-cycle system is to-day.

In regard to the 1200-volt, direct-current motor, my conclusion is that the commutation of this motor is so infinitely superior to the commutation of any alternating-current motor I ever. have seen—except one—that there is no comparison. As Mr Armstrong has stated, there has recently been developed one alternating-current motor operating on heavy overloads with absolutely sparkless commutation. It is just as good as the standard direct-current motor, or probably a little better.

Frank J. Sprague: Owing to the lateness of the hour, I cannot now reply to the various speakers, because I cannot deliver my views in sufficiently condensed form. I shall have something to say later in a written communication to be inserted in the PROCEEDINGS. I think possibly the paper has at least one merit, it bids fair to bring out some additional facts about the apparatus of both kinds. The fact remains that a good many millions of dollars have been invested on two great trunk-line systems, which will soon be in competitive operation, and there will be a comparison on these roads which none of us can gainsay.

W. S. Murray (by letter). Conscientiously I find little in Mr. Sprague's paper to discuss. This was my conclusion at the meeting; the same now. It seems to me that what is not wrong in Mr. Sprague's paper is not new. In passing, however, I cannot fail to record here my high sense of appreciation for Mr. Stillwell's and Mr. Storer's excellent contributions, not so much because they were refutations of Mr. Sprague's unalterable conclusions, but for the valuable data they contained concerning the real relations in design and practice between alternating-current and direct-current railway motors. Again, it is difficult to express the pleasure in noting the small per cent. increase in weight for equal capacity and the almost coincident curve of efficiency. These cases being the citations of the chief engineer of the railway department of one of our large manufacturing companies, and a consulting engineer who has shaped the duties of many railway motors.

It would be my wish that the smallest emphasis be placed on the efficiency of the alternating-current motor, even though its efficiency curve throughout its complete range of load were the equal of its direct-current brother. If efficiencies be considered, let us discuss the ratio of the pound of coal to the ton-mile. There is nothing electrical about this; it is within the comprehension of steam railway engineers (though it is a chain made up of electrical links); and if the ratio proves less for the alternating-current than for the direct-current system, then we have a real value that is of as much interest to the banker or director interested in the railroad as to the electrical engineer desiring its use. Would it not be better to consider the whole chain rather than one link? I welcome the new weights and the new efficiencies for their corrective (?) influences of the one-part-at-a-time man.

It was unfortunate that the photographs as originally shown in the advance copies of Mr. Sprague's paper were so poorly representative of the catenary construction. However, I am told these were the best the publication department of the Institute could produce on the very short notice they received. Those now published in the regular PROCEEDINGS are fairly representative.

T. J. Johnston (by letter): While I am quite willing to leave the discussion of the engineering features of Mr. Sprague's recent paper on methods of electric traction to professional engineers, it seems to contain (or perhaps to reiterate) an economic fallacy; namely, that the "financial factor" will determine whether a road shall be electrified, the implication being pretty plain that it, solely, will settle the question.

The process so graphically described by Mr. Sprague, by which our present enormous steam railway system was built up, is now going on before our eyes, with electric railways; that is, short lines of road are being built, cities are being connected, extensions are being made and eventually consolidated, until in many directions it is possible to take extended trips by electric lines. Awhile ago the writer rode in an electrically propelled sleeping car, the comfort of which may be imagined

The growth thus initiated will not stop short of a sufficiently complete system of electric railways; the willingness of present railway managers, or even their ability, to transform the power side of their systems need not be considered at all. If these gentlemen are unable to raise the money, they will be left with their freight business, and their passengers will be taken from them, even as now the interurban roads take all of the local traffic that is worth while, leaving the more expensive and troublesome long-distance trains as a sort of white elephant on the hands of the steam road. It will not be many years before the large cities will wholly prohibit the steam locomotive, as the Congress has practically done in Washington.

It is truly a serious situation for the railway men, with their credit hampered by foolish legislation and equally foolish popular clamor; while their electric rivals obtain privileges which no one would grant to the steam road. The problem of finding the money, and, after the money is found, of finding the available working force is truly tremendous, yet it must be solved. It is as certain as anything can be that our people want and will have electric traction on an increasingly great scale, until practically all of our passenger traffic at least is so operated. Nor will they be content with the present methods of running trains. It is amusing to see how a steam railway man with a converted road on his hands throws away the advantage of electricity and insists on running his cars in trains every two hours or so, instead of splitting up the units and running one or two cars every few minutes; for example, the Atlantic Division of the Long Island Railroad, upon which the flexibility of electric service is, during the "non-rush hours," nearly thrown away.

Lewis B. Stillwell (by letter): The paper read by Mr. Henry St. Clair Putnam and the writer on January 25 and the paper read by Mr. Frank J. Sprague on May 21 bring out an interesting and apparently radical difference of opinion in respect to the question of choice of system for electric operation of trunk-line railways. In the former the opinion was expressed that alternating-current equipment is the only class of equipment deserving serious consideration in connection with the general problem of replacing the steam locomotive by the electric motor on trunk-line railways. In the latter it is asserted that "where equal permanence of installation is provided for and equal ultimate as well as average duty there is not on demonstrated facts a wide variation in the initial cost of plant". While the position taken by the author is less radical than it was in the oral discussion of the paper of January 25, he devotes a large part of the present paper to the presentation of facts and opinions which have led him to the conclusion that the proposed 1200-volt, direct-current system is superior to the single-phase, alternating-current system.

When conclusions radically different are reached in a matter of this kind, the explanation is usually found by examining the premises respectively assumed. In this case an examination of the paper of the evening and consideration of certain facts clearly brought out in the oral discussion go far to explain why its author has reached a conclusion differing so widely from the opinions expressed by Mr. Putnam and myself.

1. It appears that the author's conclusions have been based largely upon a radical misconception of the facts as to weight and performance of single-phase, alternating-current motors as compared with direct-current motors. His reasoning is based largely upon the idea that motors of the former type weigh about twice as much as those of the latter type. As has been clearly shown in the discussion by the designing engineers of our great manufacturing companies, the difference in weight of 25-cycle, single-phase, alternating-current motors and 550-volt, direct-current motors of equal output is, in general, much nearer 25% than 100%; while the difference between 15-cycle, single-phase motors and 550-volt, direct-current motors of from 100 to 400 h.p. is still less.

The author places great emphasis upon the question of comparative motor-weights. If his view of the controlling importance of this consideration be accepted, it would appear that the reduction in the assumed ratio of weight upon which his conclusion so largely depends from 2 to 1 to 5 to 4, or less, might involve a material modification of his conclusions regarding the relative values of the contrasted systems.

2. It is evident also from the paper that its author has failed to balance accurately the inherent differences between single-phase and direct-current motors. In the light of Mr. Storer's oral discussion of this phase of the paper, the majority of the assumed disadvantages of the former disappear

3. An apparent oversight may further explain how the author has arrived at his conclusion. I refer to the fact that his paper ignores the very important consideration that in general a protected third-rail cannot be located in any position upon the existing tracks of our railways which will not involve more or less interference with rolling stock equipment. The third-rail location adopted by the New York Central, for example, makes it impossible to operate over tracks thus equipped large steel coal cars of the type now so extensively used. The New York Central has met the situation by excluding from its tracks which have been fitted up with a third-rail certain classes of rolling stock. This special solution may be satisfactory in this instance, but in considering anything like a general electrification of trunk-line systems the interference of the third-rail with rolling stock constitutes a very strong argument in favor of overhead construction.

There is nothing in this paper, nor were any facts presented in its discussion, which justify a modification of the opinion which I have expressed to the effect that the alternating-current system is best adapted to trunk-line operation. The paper under discussion uses the 550-volt, direct-current motor in such comparison of alternating-current and direct-current motors as it presents but in comparing systems substitutes the 1200-volt, direct-current motor for that of 550-volts. This substitution is materially easier on paper than it would be found in dealing with actual equipment. As a matter of fact, the so-called 1200-volt, direct-current system to-day does not exist except on paper; and while there is no doubt that it can be developed into a working system the paper under discussion ignores difficulties in the way of its development and application more weighty than any which to-day stand in the way of the complete development of a 15-cycle, single-phase system.

The New York Central has equipped its terminal with direct-current apparatus operating at about 600 volts, and has done so for reasons which probably were valid at the time the decision was made. It is conceivable that other railways in equipping terminals may be led by local considerations to adopt the same system. In the light of the discussion of this paper, however, it is difficult to conceive circumstances under which engineers would be justified in advising the use of 1200-volt, direct-current equipment in the electrification of a terminal or short division of railways now using steam locomotives. The author of the paper has advised the New York Central to use 600-volt, direct-current equipment in electrifying its New York terminal. He intimates that if called upon to do so he would advise the Pennsylvania Railroad to use 1200-volt, direct-current apparatus for the equipment of its line between New York and Philadelphia. Were this division of the Pennsylvania system to be electrically equipped to-day, it would be done for reasons which a few years hence will apply with almost equal force to the company's lines between Philadelphia and Pittsburgh. The present state of the art as evidenced by the facts set forth in the discussion of this paper and of the paper presented on January 25 justifies the statement that for the electrification of even short divisions the 15-cycle, single-phase alternating-current system at the worst is not inferior to the 1200-volt, direct-current system. The comparative advantages of the former, of course, increase very rapidly with decrease in frequency of service. Under conditions of average steam railway service in the United States, which were the conditions discussed in the paper presented by Mr. Putnam and myself on January 25, the first cost and the annual cost of the 1200-volt, direct-current system as compared with the single-phase, alternating-current system practically prohibits the adoption of the former. In view of these facts it would seem that there is no place for the 1200-volt, direct-current system in connection with the electrification of any part of our trunk-line systems. The 600-volt, direct-current system will do the work satisfactorily in electrifying a terminal. Only the alternating-current system is applicable, as the author of this paper himself suggests, to "roads of considerable extent which operate an irregular and sparse traffic". Between these two there is no sufficient reason to justify the introduction of a third-rail system which does not pretend to solve the general problem, which can be used only on tracks from which certain classes of rolling stock are excluded, and which inevitably would introduce additional complication and interference with the ultimate standardization of electric railway equipment.

Frank J. Sprague (by letter): The comments on my paper have been varied and interesting, sometimes illuminating, but again marked by more of criticism than candor, and offering less of proof than affirmation.

I did not attempt to solve the problem of electric operation of trunk line railways, but rather to set forth some general problems, and certain technical facts as I have found them by somewhat careful investigation.

I have been taught by a modicum of experience that the electrical engineer is apt to approach the larger problem of railway electrification with a superabundance of confidence, undiluted with practical and necessary experience in that particular field. It has seemed necessary to utter a warning against too great a measure of self-reliance, too positive prophecy, and to indicate some of the difficulties in the way of achievement.

I prefer to deal with facts, not theories; performances, not promises; and where these are at variance, it is essential that the differences should be pointed out. I am, for special reasons, probably more anxious than most members of this Institute that railway electrification shall prove acceptable and beneficial, and I welcome every advance, no matter through what channel, which can contribute one iota to that end. So long as equal results are attained, it hardly seems necessary to emphasize the fact that simplicity is a desideratum of the utmost consequence, and I should be glad to eliminate every piece of apparatus between a central station and a motor which does not prove essential to operation.

If I express some measure of disappointment, it is because of the fact that in spite of all the work done, and my own hopes as well, more has not already been accomplished in the single-phase, alternating-current motor development, and that neither it—nor for that matter what has been done with high-potential direct-current motors—warrants approaching the general railroad problem other than with diffidence and hope, and makes us doubly obligated to urge the utmost progress along whatever path may offer any advantage whatever.

Whatever my beliefs, I cannot but chafe at the slowness of advance, and the subordination of development on the one hand to a fixed ambition, and on the other hand to commercial catholicism. I doubt if any member of this Institute questions how quickly and radically I would demonstrate my own confidence in future possibilities if the companies which have borne my name had not been swallowed up in the sea of modern consolidation, instead of my now being obliged to content myself with academic pleas for intelligent expansion.

Quite possibly I have not fully understood the purport of Messrs. Stillwell and Putnam's interesting paper, but if so, then I have company in such misunderstanding. While it is true we are not in entire accord, we are not entirely in disagreement; for I note that Mr. Stillwell accepts historical facts, and is even tolerant of my generalities. We do disagree, it seems, in one important essential at least. He has "nailed his flag" to a 15-cycle mast, guyed by an overhead trolley wire, for trunk-line service. I have gently remonstrated, and being something of an agnostic, have said "I don't know"—venturing the opinion, with which I am quite sure in the end most practical railroad men will agree, to say nothing of a large body of the electrical engineering fraternity, that no present standard can be safely adopted to the exclusion of everything else. Such a decision would be not only a bar to evolution in the development of the application of electricity to railways, but a final expression of opinion that invention is at an end, and that the dicta of engineers can decide or change the inevitable exercise of individual thought, and curtail the activities of competitive manufacture.

Mr. Stillwell lays much stress upon the "conditions of average steam railway service in the United States." The average conditions, measured financially, do not, in my judgment, permit of electrification, which conclusion I have tried to make clear, and which is not altered even if I have not succeeded.

I feel particularly indebted to Messrs. Wilgus and Henderson, the former of whom, in his executive position, has had immediate charge of a great electrical development, and both men of wide practical railroad experience, for their common-sense and illuminating comments from the standpoint of the steam railroad man, because our tendency as electrical engineers is to discuss with too much detail the technique of our profession.

Now and then in our art, as in all others, some one not too closely face to face with technical problems coins a laconic phrase, which one instantly recognizes as expressing the truth in a nutshell, and as a crystallization of his own ideas on the subject, and then he wonders why nobody thought of it before. Such a phrase, and a particularly apt one, is that of Mr. Wilgus', "evolution, not revolution". It is the concrete description of the progress in the electric railway industry since its beginning, and it is expressive of what it will be in the future.

In studying different motors, it seemed wise to expand previous methods, and to adopt one capable of wide application. Inasmuch as it was impossible within the limits of a paper already too long to apply this method specifically to all makes and sizes of motors, I contented myself with selecting one especially typical example of direct-current and 25-cycle, alternating-current motors, supplementing the details of this comparison by some specific facts about other machines, namely, the smallest on regular interurban service, and the largest in present locomotive service, presumably a sufficiently wide range for illustration of certain facts, leaving the application of the specific method to any other case of interest to an engineer.

In comparing capacities, it is eminently proper that the *weight-efficiency* of electrical equipments should be based upon each of two conditions: first, the total weight of motors and any connecting device necessary to transmit the power of the motor to the axle, this weight, if the trunk frame forms a part of the motor, including such additional part as is necessary over and above that required for structural purposes; and secondly, the total amount of electrical apparatus as above determined, plus every device for collecting current or controlling the motors carried upon the car or locomotive.

Mr. Stillwell holds that I should compare motors of equal capacities, not of equal weights and dimensions, and states that since the weight-coefficients of all motors, of whatever make or type, increases with the size, there would not in such a comparison have been so great a disparity. Quite true, but the error of this reasoning is apparent if one reverses his proposal, and compares an alternating-current motor of a given physical dimension with a direct-current motor of larger physical dimensions and weight. What a disparity would then appear! I do not know that I am particularly surprised at the remonstrance which meets the actual comparisons made in the specific instance illustrated, for the method intelligently applied is sufficiently instructive for those who wish to know the facts to find further application. The meaning and the force of the comparisons will not be brushed aside by *ex-parte* statements of isolated and uncorrelated facts, or by such a criticism of specific motor weights and capacities as distinguished Messrs. Stillwell's and Storer's comments, somewhat unwarranted in view of my specific statement that the motors were " both standard modern machines ".

In order to avoid any just criticism of the curves submitted, I selected not only standard modern machines of practically identical weight, but machines built by the same manufacturer, tested under like auspices and by identical methods, and by experts who had no thought that the machines would ever be compared in the matter I have shown. Not only are these machines of similar weight, but they are almost exactly of the same dimensions, of the largest practical size which should be put on a truck with a 33-in. wheel, and as large as should be used with a 36-in. wheel when running in the open on a standard railroad. Gear and transformer weights were, as stated, eliminated.

That an erroneous conclusion might be expressed in comments based upon a hasty and cursory perusal of a paper is understandable, but that it should be allowed to stand after opportunity to ascertain the facts suggests either great preoccupation.

or a hiatus in memory. It is a wise father who is not ashamed of an adopted child, and I cannot but regret that Mr. Stillwell has so long failed to recognize, in motor *X*, whose weight, as well as speeds and capacities throughout a thermal range varying from two-thirds of an hour to five hours were given with exactness, a machine for which he is largely responsible. Its characteristics are based upon the official technical reports of the General Electric Company, the builders of this G. E. 69 *B* type for the Interborough Rapid Transit Company, on Mr. Stillwell's general specifications, 418 of these machines now forming part of the equipment of that road. They are sometimes "rated at 200 h.p. at 300 amperes", but actually test to 241 h.p. with 75° rise of temperature, according to the standard practice of the American Institute of Electrical Engineers. Several hundred more of these motors are in use on the London underground railways, and 268 motors of similar frame, known as the G. E. 69 *C*, built for 50 volts higher normal operation, nearly 100 less revolutions at the one-hour rating, but developing, notwithstanding, 232 h.p. with like rise of temperature, are in use on the New York Central Railroad. Type *Y* is the G. E. A. 603 25-cycle, alternating-current motor, and illustrates the largest of this type of machines built for motor-car work.

Call these machines what one will, by any name which may smell more sweet, the comparisons are on identically the same basis, therefore absolutely proper; and in all fairness comparisons of any machines should be made with identically the same kind of data. When so made, Mr. Stillwell's pyramid may be inverted, and landed on its base where it belongs.

A similar direct-current motor when equipped with commutating poles weighs about 400 lb. more, but in view of a remarkable freedom from sparking it can with perfect impunity be steadily operated at an increase of potential which will much more than offset the increased weight. As an example of what can be done with this type of machine, I have seen a standard motor of 75 h.p. commutator capacity, temporarily fitted with commutating poles, operated with an increase of 80% in voltage, and develop over 250 h.p. without a sign of distress. Of course this is unusual, and ordinarily prohibitive on account of the speed of the machine, but it illustrates the possibilities of an improvement which I have so steadily urged, and which in now being adopted has so largely augmented the allowable working direct-current potentials. If Mr. Storer will compare on the thermal basis a quadruple motor equipment of this type with an equipment of 25-cycle, alternating-current motors of like permissible speeds and weights, the comparison will be somewhat instructive.

With regard to 15-cycle motors, I enumerated with a good deal of particularity certain advantages which they individually offered as compared with the 25-cycle motor, and especially the increase of capacity. I assume there is here little room for disagreement; but granting the full measure of these advantages, variable in the matter of capacity according to the nominal rating, and the ratio of load to that rating, it seems quite apparent that the increase in weight of the transformer will largely offset the saving in motor-weight capacity. Inasmuch as we are concerned not alone with motor weights, but with the total weight which must be carried by the individual drivers, and within allowed wheel-bases, this offsetting of the saving in weight in one part of the equipment by an increase in the other cannot be ignored; and the question properly arises whether the advantages are sufficient to warrant the adoption of the standard in spite of many well known objections.

It is a curious commentary upon the futility of prophecy, that within a month of the announcement of the necessity of a new standard, and within the hour of its repetition, the responsible technical engineers of a great manufacturing corporation voice, not only for themselves but for a great portion of the engineering world, their disapproval of its adoption, and in the same breath announce a radical advance in 25-cycle motor construction which maintains the merits of a higher frequency, and removes one of the reasons for lowering it.

Comparisons based upon motors designed, but not built, are essentially unsatisfactory, and of course they will be more or less at variance, depending upon the size and make of motors selected. The 15-cycle, single-phase, alternating-current motor is too new a machine to have any record behind it. In my paper I compared the weights of certain standard quadruple motor suburban equipments, designating the motors *A* and *B*, the former for 15 and the latter for 25 cycles, the weights being those officially given by the manufacturers. These motors were of competitive makes, the former being the Westinghouse and the latter the General Electric, but, as I stated, I did not deem the weights given as final. It will be therefore perhaps interesting to know that, eliminating the element of competitive manufacture, and comparing recently given official weights of 15- and 25-cycle equipments made by the former concern, there is an excess of total weight of a quadruple equipment of nominal 75 h.p. motors greater than that given in my paper.

Certain features of the New York Central and the New Haven machines have been given so frequently that it is unnecessary to refer to them further at the present moment, except to state that their weight-coefficients are very different, and much in favor of the former machines. When large 15-cycle alternating-current, and other types of direct-current locomotives are built, there will be an opportunity to make further comparisons on a like basis. It may be interesting to note here that the recent decision to adopt three-phase locomotives on the Cascade Tunnel was because of lack of guaranteed capacity of 15-cycle motors.

Mr. Stillwell says that I do not pay sufficient attention to the cost of the intermediate link between the generating station and the locomotives. I will endeavor to add some information bearing on this point.

The New Haven electrical equipment comprises 35 locomotives weighing 93.3 tons each, or a total of 3266 tons. with an aggregate capacity of 35,000 h.p. on the hour rating. Considering the individual capacity, the number of machines which will be under repairs, the time in the shop and other lay-overs, I believe that not over 23 of the New York Central machines would be required to do the work of the 35 New York, New Haven and Hartford ones. The New York Central locomotive weighs 95 tons, which will make a total of 2185 tons, with an aggregate capacity of 50,600 h.p. The difference in total weight is 1081 tons, and on an assumption of an average duty of even 200 miles per day there would be an excess of 216,200 daily locomotive ton-miles on the New Haven system. The difference in the cost of the above locomotives would ordinarily be about $400,000. The total distance from Stamford to the Grand Central Station is 33.48 miles, 21.45 miles comprising the single-phase section. As I have pointed out in my paper, the direct supply to the overhead line from the main station is but a special provision; it does not mark any wide application, for step-up and step-down transformers will be absolutely necessary as a general rule. Therefore, for comparison, we may assume on the New York, New Haven and Hartford the presence of those transformers. The introduction of synchronous converters in addition, assuming the same number of sub-stations, would add about $15 per kilowatt of normal capacity, so that the $400,000 differential in locomotive costs would provide for a synchronous converter addition of 26,667 kilowatts, which would have a temporary excess capacity of anywhere from 100 to 200%, according to the specifications of the engineer and the zeal of the manufacturers.

But this is not all. In a letter addressed to Mr. W. H. Newman, president of the New York Central, under date of Oct. 27, 1905, and published in the technical press in December of that year, in which the abandonment of the system then being introduced, and the adoption of the single-phase alternating-current system were urged, one of the principal reasons given was a great saving in cost of the working conductor system, which it was claimed would aggregate $9,000,000 between New York and Buffalo on the Central's line alone. The actual difference in the number and cost of equipments which would be required was ignored. The estimate per mile of road of a four-track line, with catenary construction from bridges over the tracks, and with operation at 6000 volts, exclusive of transformers, was given as $12,436. Some time afterward an estimate was published purporting to give the cost of the New Haven installation, which with additional provision of an extension of the bridges to cover six tracks instead of four, but not including the additional overhead work, was stated to be $27,000 per mile of road, although with operation at 11,000 volts. A careful analysis of actual construction makes this, according to Mr. Wilgus' statement, probably over $50,000 per mile, which I assume is exclusive of any lowering of tracks, clearing of right-of-way from trees, or work in connection with telegraph or telephone circuits. The cost of the working conductors of a third-rail system for four tracks, the protected under-contact rail being used, supplemented by a main conductor so that any of the tracks can be cut out, is much less than this.

Looking into the matter soberly, then, it would seem that in the first really comparative examples on a large scale, the cost of the working-conductor construction of the alternating current system as actually erected is considerably higher than that of the third-rail construction, when installed on a trunk-line railroad in operation, and also that the cost of equipment to do equal work is much higher, this latter difference alone being enough to pay for a great abundance of synchronous converter apparatus.

Just here, I may be permitted to suggest that it savors of trespass beyond the proper limits of a discussion of my paper when one assumes what my decision would be in the event of my opinion being asked as to the equipment of a trunk line division. Whenever such decision may be necessary, it seems reasonable to suppose that I shall be guided by the particular railroad problem under consideration, the real interests of my clients, and the then known or probable development in the art quite irrespective of what my decision might have been at some other time and under other conditions.

It seems necessary to emphasize the meaning of restricted capacity of equipment for any allowable truck dimensions and unit wheel-weights. I repeat that it is a matter of no vital concern that 20 or even 40 tons be added to the weight of a freight train with any given motor capacity, especially on low-grade roads; but it is of the utmost importance if either the same capacity can be got with fewer units, or if, on the other hand, the excess weight will give even 50% more continuous capacity. What is required in any locomotive is simplicity and capacity; simplicity, to avoid an acute attack of appendicitis when far from home, and capacity, to meet the inevitable overload demands which will be made upon it by the operating force and the exigencies of service. This latter quality has been the constant aim of every superintendent of motive power, every general manager, and every locomotive builder. Larger cylinders and boilers, increased tube and grate surfaces, and more capacious fire boxes—all demanding greater weight on wheels, continually opposed by the limitations of bridges, rails, and ballast, and disheartening to the engineer of maintenance and way.

Need there be any more eloquent and forceful, nay, vital plea for keeping down wheel-weights, both individual and as concentrated on bridge members, especially when running at high speeds, than the appalling number of rail breakages reported during the past winter, and the recent attack upon the sufficiency of rail-sections and the integrity of rail manufacture—all emphasized by the Carnegie company's report of 20 broken rails after a single trip of the Pennsylvania's 18-hour flyer to Chicago!

On the subject of costs, we should be somewhat chary in formulating conclusions based upon assumed prices for electrical apparatus. At a former meeting of the Institute, unit and differential prices were given for 15- and 25-cycle electric locomotives. Mr. Stillwell based his calcluations on $25,000 per locomotive for 25-cycle operation, with a possible reduction of $1,000 for 15-cycle equipments, this latter difference being enlarged to $5,000 per unit by Mr. Storer. Little reliance can be placed upon such figures when it is well known that for various causes, such as changes in price of labor and material, variation in types of motors and locomotive design, the use of alternating-current or direct-current apparatus, etc., the unit price of various locomotives within the last three years has varied, not $1,000 or $5,000, but over $25,000, and the actual capacity of the highest priced locomotives has been less than that of lower priced ones.

Mr. Storer has favored the discussion by several positive statements, and certain figures giving the apacities and efficiencies of various types and sizes of motors. As presented, these are interesting but not conclusive; I submit that it is impossible properly to discuss them unless sufficient data are given to analyze them on the thermal basis after the manner I have indicated. There is nothing mysterious about it; and if in addition to the thermal curves, there are submitted the detailed statements of the weights of apparatus which go on a car or locomotive, we will be in possession of that much needed information urged before the standardization committee of the Institute as essential to a full understanding of machine performance. Engineers need the facts, but they should be complete, not such selected ones as manufacturers are sometimes inclined to submit for digestion.

Reference to the relative torques attained by continuous and intermittent currents is unfortunate, for if there is any characteristic of single-phase operation which is particularly noticeable, it is the slow acceleration of cars equipped with such motors; in other words, the lack of motor torque with equal gear reductions. The reasons are too well known to waste time discussing them. Mr. Steinmetz very aptly puts the case in a nutshell when he states that no matter how good a single-phase alternating-current motor is, when put on a continuous-current circuit it is a better motor, and it then becomes possible to re-design a machine to get more capacity out of a given weight, or less weight and less cost of construction for a given capacity. Possibly the self-repairing characteristic of the motors referred to by Mr. Storer may be explained by the fact that, weakened by an alternating current, they broke down when put on to a grounded circuit, and when put on to a lower potential metallic circuit they managed to function.

It is a new theory in mechanics that reduced clearances and allowable wear of working parts is preferable to ample latitude in these matters. With regard to gears, it is quite possible that on the motors with which he is acquainted the same gear-pitch is used on slow-speed direct-current motors and high-speed single-phase motors. It might occur to one that permissible strength of parts in one case is sacrificed to the manufacturing requirements of the other.

I confess to a stenographic error in the matter of the minimum number of poles on single-phase motors. Of course, most people know that four instead of eight poles are used on certain sizes of motors; but there are other manufacturers, and 14-pole machines have been proposed.

It is quite true that locomotives are not intended to stand still; Mr. Storer remarks that they are intended to move. Undoubtedly, but it is likewise necessary to start a train, or perhaps hold one on a grade, and there are times when a machine, if a part of the equipment fails, may be called upon to stand very considerable periods of steady pulling without actually turning, and certainly great overloads. A little greater familiarity with practical railroading would perhaps show him instances in which locomotives are really not intended always to go, but sometimes actually stand still and push, and keep on pushing. A case in point is the operation of freight trains on long up-grades, where the helper locomotive, well back from the head of the train, is frequently called upon, when the leading locomotive pulls up on signal, to hold the train with full head of steam against slackened draw-bars, and to prevent it being pulled in two when the leader starts again.

It will not do lightly to dismiss the New York Central type of machine from further discussion, or possible notice, by remarking that there is but one single installation of this type. That is quite true, but it happens to be the largest electric locomotive installation in the world, and this particular group of machines is now probably doing more work than all other electric locomotives of trunk-line size which have been built in the United States in the last twenty years. It is, therefore, a machine which must be seriously reckoned with.

Mr. Scott seems to favor alternating-current braking by return of energy to the line, and even claims it to be more effective than direct-current braking on a closed circuit. His present attitude on the subject is a reversal of position assumed but a short time ago by his associates; but this is in accord with the change of heart on multiple-unit operation and commutating-pole railway motors.

In referring to the discussion of Mr. Carter's paper before the Institution of Electrical Engineers, I did not state it as a fact, or my opinion, that there is 10% lower electrical efficiency in a single-phase motor as compared with the direct-current current motor, but quoted Mr. W. M. Mordey, a well known advocate of single-phase apparatus, and for the purpose simply of illustrating the fallacy of assuming that the location of the excess loss, no matter how much, is a matter of indifference.

Of course, as Mr. Scott says, by varying the voltage taps on a transformer, the speed with any given torque can be reduced below that corresponding to the maximum working potential. I might add that the capacity is reduced in the same ratio, and there would be little effect upon the comparison of weight-coefficients.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907.

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RELATIVE MERITS OF THREE-PHASE AND ONE-PHASE TRANSFORMERS

BY H. W. TOBEY

During the last few years there has been a gradually increasing tendency in this country toward the use of three-phase transformers on three-phase circuits instead of groups of three, or in some cases two, one-phase units. It is the purpose of this paper to outline briefly these two systems, and to point out as far as possible the important features of both, with their advantages and limitations.

In this country, particularly, there is a strong feeling among many engineers in favor of single units. This feeling is probably due in part to the fact that if one transformer in a group gives trouble it can be readily removed and replaced by a reserve transformer or if no reserve is at hand the load can be carried by the remaining two, if delta connected; whereas if one phase of a three-phase transformer gives out the entire transformer is rendered useless. Where the plant is small, this feeling is more or less justified on account of the fact that an extra three-phase transformer, because of the additional expense, would be out of the question, whereas the cost of an extra one-phase transformer would not be serious.

Where the plant is fairly large, the saving in cost introduced by installing three-phase units makes possible the providing of an extra transformer for reserve. Moreover, if no reserve is available it is possible, in the case of shell-type transformers at least, to take an injured phase out of commission and operate the remaining two phases in open delta until the necessary repairs can be made. This is done by means of an arrangement recently announced, in which both primary and secondary windings of the injured phase are cut out and short circuited on themselves. As mentioned, this method applies only to shell-type transformers connected delta primary and secondary.

From the foregoing, it would seem that as far as reliability is concerned the two systems are about equal.

As to initial cost, the three-phase transformer has a distinct advantage. Not only is it possible to utilize the iron in the magnetic circuit to better advantage, but a saving is also possible in the cost of the containing tank, inasmuch as only one is required instead of three. All things considered, the cost of a three-phase transformer may be taken as about 85% of that of three of the one-phase type—total capacity, frequency, and voltage being the same of course in both cases.

In addition to the initial cost, there is also a saving in material and labor incurred in connecting up the transformer for service. With the three-phase type, all interconnections between phases are made within the containing tank or case, thus leaving but three high-tension and an equal number of low-tension terminals with which to connect outside lines. For installation, therefore, the total amount of cable required is less, the connections are simpler, and consequent danger of error less with the three-phase transformer than with several one-phase transformers. The expense of isolating compartments is also much reduced, it being customary in many plants to provide a separate berth for each unit.

While general appearance is not necessarily a controlling feature in a transformer building, it is nevertheless to be considered, and here again the three-phase transformer with its simple connections would look neater and more symmetrical than would three one-phase units.

Floor space and height are features which in stations of limited area require careful consideration. In these regards the three-phase transformer has distinct advantages, as a saving of at least 30% can be attained in floor space. and usually its height is somewhat less than that of the one-phase unit.

As regards regulation, neither system can claim an advantage. Both regulate equally well on balanced and unbalanced loads, whether these are inductive or non-inductive.

In some plants the question of limited facilities for handling would be a deciding factor. Here then the choice would be in favor of one-phase units, on account of their decreased weight and dimensions.

For extremely large three-phase units it is probable that some system of forced-oil circulation would be adopted, as by this means the large coils and extremely large mass of iron necessary to form the magnetic circuit may be cooled without difficulty.

In small transformers suitable for pole suspension, the advantages of the three-phase transformer are emphasized in appearance and reduction in weight.

In general, the two systems may be summed up as follows: where the plant is of small or medium size, the facilities for handling limited, and the floor space not an important feature, groups of one-phase transformers would, without doubt, be adopted. For large plants, however, having ample facilities for handling, and particularly where floor space is a question of importance, the three-phase type would be most suitable.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 21, 1907.

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RELATIVE ADVANTAGES OF ONE-PHASE AND THREE-PHASE TRANSFORMERS

BY JOHN S. PECK

In considering the relative advantages of three-phase and one-phase transformers, it will be assumed at the outset that the three-phase transformer is to be compared with a group of three one-phase transformers whose aggregate output is the same as that of one three-phase transformer; for it will be admitted at once that a comparison between one one-phase transformer and one three-phase transformer of the same output would be all in favor of the one-phase transformer. On this assumption, the advantages of the three-phase transformer over the one-phase group are as follows:

1 Lower cost.
2 Higher efficiency.
3 Less floor space and less weight.
4 Simplification in outside wiring.
5 Reduced transportation charges and reduced cost of installation.

The disadvantages are:

1 Greater cost of spare units.
2 Greater derangement of service in the event of breakdown.
3 Greater cost of repair.
4 Reduced capacity obtainable in self-cooling units.
5 Greater difficulties in bringing out taps for a large number of voltages.

The various advantages and disadvantages enumerated above will be considered in sequence.

ADVANTAGES

1 *Lower Cost*—A three-phase transformer should always be cheaper to manufacture than three one-phase transformers of the same total output; for, by combining one-phase units into a three-phase unit, there results a considerable saving in active material due to the magnetic phase relations. Also, there is only one containing case, one set of end-frames, one cooling system, etc., to be provided for the three-phase unit.

The labor is also less, not only on account of there being less active material to handle—one case, one set of end frames, etc.—but because the unit as a whole is larger, and there is always less labor cost in manufacturing one large unit than there is in manufacturing several small units for the same total output.

2 *Higher Efficiency*—Since there is less active material in the three-phase transformer than in the one-phase group, the loss at the same densities will be less, and therefore the efficiencies higher, consequently the total radiating surface required may be less.

3 *Less Floor Space and Less Weight*—This follows from a consideration of 1 and 2.

4 *Simplification in Outside Wiring*—The star or delta connections of a three-phase transformer are simply and easily made inside the case, for as a rule only three high-tension and three low-tension leads are brought out; whereas with three one-phase transformers at least six high-tension and six low-tension leads are brought out and the transformers interconnected by suitable wiring.

5 *Reduced Transportation Charges and Reduced Cost of Installation*—The lighter weight and less bulk of the three-phase transformer will, in general, result in reduced transportation charges especially where shipment is made by water. This advantage is open to question, however, when there are long wagon hauls over mountain roads, with poor facilities for handling heavy machinery. In this case it may be cheaper to transport a greater weight and bulk in small units; but in general the transportation charges should be considerably in favor of the three-phase transformer.

It should also be noted that in many foreign countries duties are charged according to the weight of material, but whether duties are charged according to weight or price, the advantages are with the three phase transformer.

In general, it will be cheaper to install one large unit than three small ones. This is particularly true where the transformer must be dried out on the site by heating or by a vacuum process.

DISADVANTAGES

1 *Greater Cost of Spare Unit.*—It is obvious that any three-phase unit having three times the capacity of a one-phase unit will cost considerably more. This may be of some importance where there is but one three-phase unit, but it will be found that in many cases the cost of two three-phase transformers with a total capacity of 200% will be but little more than that of four one-phase transformers having a total output of 133%. Where there are several similar three-phase units, it will be found that the reduced first cost of adopting three-phase units will more than pay the difference in cost between the three-phase and the one-phase spare unit. In addition, there is the advantage that the three-phase spare unit will have three times the capacity of the one-phase spare unit.

It should be noted, however, that, with a three-phase or one-phase core-type transformer, there is much less need of carrying a complete spare unit than with the shell-type one-phase or three-phase transformer. This is on account of the very simple construction of the core-type transformer, and the ease with which it may be repaired. The top-yoke is built up in one solid piece and bolted down with butt joints to the three vertical cores. Thus it is necessary in case of repairs to loosen only a few nuts, remove the top yoke, slide off the damaged coils, and replace them with new ones; bolt down the yoke and replace the transformer in position. Should the laminations be welded together, it might be necessary to do considerable filing, but in general there is less chance of burning the laminations than with the shell type of construction. With a supply of spare coils, any ordinary burn-out should be repaired in a very few hours. On the Continent, it is quite customary to use core-type three-phase transformers with only coils as spares even for very important work; for it has been found in actual practice that repairs can be made in but little more time than is required to replace one transformer by another.

With the present standard shell-type of construction, a much longer time is required for repairs, on account of the fact that the laminations must be removed and replaced a few at a time. The repair of a three-phase shell-type transformer is so serious an undertaking that it would probably seldom be attempted on the site but the transformer would be returned to the manufacturer.

2 *Greater Derangement of Service in the Event of Breakdown*—When three one-phase transformers are connected in delta on both high- and low-tension windings, one of the three may fail and be cut out, and the remaining ones will continue to carry about two-thirds the total load without overheating. With the star connnection on either winding, this cannot be done. A three-phase core-type transformer cannot be operated with a short-circuit on any phase. The three-phase shell-type transformer may be operated, however, with a short-circuit on one phase provided both windings are in delta; but, while this may be used as a temporary expedient for carrying partial loads, the whole transformer must be removed eventually for repairs.

In any event, whether core- or shell-type transformers are used, there will be probably a somewhat greater delay in substituting a three-phase spare unit than in substituting a one-phase spare unit.

3 *Greater Cost of Repair*—With three one-phase units it is probable that in the event of breakdown in one, it will be cut out before the others are damaged. With a three-phase unit, where the phases are so near together, there is the possibility that a breakdown in one-phase may damage one or both of the others. In such event, there are two or three phases instead of one to repair; but in any event the repair of a three-phase transformer will be in general more expensive than the repair of a one-phase transformer of the same type.

4 *Reduced Capacity Obtainable in Self-Cooling Three-Phase Units*—In some cases it is highly desirable to use only self-cooling transformers. 1500 kw. is approximately the maximum size of a three-phase transformer that, with present methods of construction, can be made self-cooling. A group of three one-phase self-cooling transformers can be built with an output of two or three times this amount. Thus, if an output greater than 1500 kw. is required, it will be necessary to use two three-phase transformers, a more expensive arrangement than three single-phase transformers. It is very seldom, however, that an output greater than 1500 kw. is required from a self-cooling transformer. When artificial cooling is permissible, the three-phase transformer may be built for any desired capacity.

5 *Greater Difficulties in Bringing out Taps for a Large Number of Voltages*—The increased difficulty in arranging the three-phase transformer for a large number of different voltages might in some cases prevent its use, but such cases will be of very rare occurrence and need scarcely be considered.

To sum up, it may be said that the three-phase transformer has certain real and positive advantages over the one-phase type, while its disadvantages are chiefly those which result in the event of breakdown—an abnormal condition which occurs at rarer and rarer intervals as the art of transformer design and manufacture improves. It is the writer's belief that, as on the Continent, the three-phase transformer has already superseded the one-phase in most cases so in America and Great Britain the use of the three-phase transformer will show a very rapid increase within the next few years.

It is also the writer's opinion that a three-phase core-type transformer having as good or better performance than the shell type can be built for less money. This, together with the fact that the core type can be repaired so readily, makes it more desirable than the shell type.

In the above discussion, the three-phase transformer has been compared with three one-phase transformers, but it is possible to use two one-phase transformers with the V or T connection for three-phase working; and, by placing the two in the same case, a considerable saving in cost over three separate transformers may be effected. On account of the phase relations of the currents, however, the capacity of each transformer must be 15% greater than half the capacity of the three-phase transformer, with a corresponding increase in cost and losses.

There is another serious objection to this arrangement, for on account of the out-of-phase relation of voltage and current the voltage across the three phases will not remain in balance as the load comes on.

It is also open to very serious doubt whether this transformer can be built as cheaply as can the three-phase core type. The writer does not believe that this type will ever come into very general use.

DISCUSSION ON "RELATIVE MERITS OF THREE-PHASE AND ONE-PHASE TRANSFORMERS," AT CHICAGO, ILL., MAY 24, 1907.

Peter Junkersfeld (by letter): A decision as to the use of three one-phase transformers or one three-phase transformer should take into consideration all local conditions. The five disadvantages enumerated by Mr. Peck will in some cases be so great as to prohibit the use of three-phase transformers; in other cases these disadvantages may be negligible.

In a small system, or in any system in which the total number of units are few, the "greater cost of spare units" and "greater derangement of service" often throws the balance in favor of three one-phase transformers. However, the troubles with, or breakdowns of, three-phase transformers have perhaps been less than is generally supposed.

The Chicago Edison Company had in service on May 1, 1907, about 42,000 kw. of three-phase transformers, which type it has installed exclusively in connection with synchronous converters during the past six years. The one-phase transformers installed previously for converters aggregate about 8,000 kw. The company also has in service as step-up and step-down transformers for generators or lines a total capacity of about 6000 kw.

In reviewing the ten years' experience in which the one-phase transformer capacity has grown to 14,000 kw., and the six years' experience in which the three-phase transformer capacity has increased to thirty-two units varying in size from 550 to 2200 kw. and aggregating 42,000 kw., we have found that the total number of "troubles" where transformers have been taken out of service have been less with the three-phase than with the one-phase transformers. In fact, there was only one case worthy of notice with three-phase transformers, and even in this the damage was not serious. The one-phase transformers varied in size from 100 to 500 kw., some oil-cooled and some air-blast.

A fruitful source of transformer troubles are the taps for various voltages and the wiring inside the top of the transformer. The above mentioned three-phase transformers were not adopted until the system was so well developed that a great multiplicity of taps was no longer necessary. This, with the particular attention paid to the wiring inside the top of transformer, accounts partly for the few troubles with the three-phase transformers. The latter also embody all of the latest developments in transformer design known, having been in service little more than six years, while some of the one-phase transformers have been in service for a much longer period and are thus of earlier design.

In small and often uncertain undertakings, and in pioneering or extraordinary extension work, there are cases where three-phase transformers should not be used. The advantages of three-phase transformers are, however, so great and the results obtained are so good, both in this country and in Europe, that the use of three-phase transformers merits the most careful consideration in every case. The undertaking that is small to-day may become large to-morrow, and the growth or change in condition usually makes the situation more favorable for the three-phase transformers.

R. F. Schuchardt: Our experience has been of such a nature as fully to justify the decision made six years ago to adopt the three-phase transformers in our converter sub-stations. Where the installation is connected to an overhead line, or where the units are small in number, the situation is, of course, different. I refer to an installation such as ours where the system is very large and has underground transmission lines throughout. The disadvantages enumerated by Mr. Peck almost entirely disappear in such a system. Taking them individually:

" Greater cost of spare unit ". An individual unit being only a very small portion of the total installation, the expense is comparatively small and the saving due to use of three-phase transformers will more than offset this.

" Greater derangement of service in the event of breakdown " and " Greater cost of repair ". The transformer breaks down so seldom that one can very well afford to take the risk, especially in view of the advantages.

" Reduced capacity obtainable in self-cooling three-phase units ". Units of this kind are not generally used self-cooling. A blower system is usually installed in order to get greater capacity out of the apparatus.

" Greater difficulties in bringing out taps for a large number of voltages ". As Mr. Junkersfeld has said, the transformers are now so well standardized that a large number of taps are not required. We do not even avail ourselves of the advantage to be obtained, in case of part breakdown, by having the delta connection on both primary and secondary. We connect the secondaries in star and then join the star points together and to the neutral of the three wire direct-current system. The converters thus also serve as balancers.

C. W. Stone: Most of the discussion seems to be based upon the larger size units. I think that we ought to consider the small unit for pole work. I think this is one of the places where three-phase transformers are particularly well adapted. On poles we are always crowded for space, and that is where we need the smallest unit that we can get for the maximum output. That means the three-phase transformer.

Another point, which has not been mentioned at all, is the underground circuit in manholes. I do not think there is any place more crowded or any place that gives more trouble than the apparatus installed in the manhole. Therefore the three-phase transformer is particularly good in that place because the connections are so much simpler, and the trouble in the manholes comes principally from a poorly made connection. In a three-phase transformer there are fewer of them and therefore less chance of poor work.

In large size units in large stations the question is not so much the question of cost of spare unit as it is the question of the design of the station. Frequently transformers are left until the last thing. The transformers and the switchboards are always left until after the station is designed, and then we have to tuck them away in some corner. Therefore the question is reliability. The extra cost of spare apparatus, etc., does not come into the question at all. It is a question how much we can get in the smallest possible space. There again we have the three-phase unit. As far as reliability is concerned and the cost of repairs, I think Mr. Schuchardt and Mr. Junkersfeld pointed that out very well. The total percentage of breakdowns and the total necessity for repairing is so small that I do not think it ought to come into the question at all. The three-phase transformers do not burn out any more than the single-phase. In fact, the burn-outs are so few that we can disregard them entirely.

There was a question in Mr. Peck's paper about operating the three-phase transformer with a Y-connected secondary, stating that with the delta connection we could operate with one phase cut out and operate the other two on open delta. This is also being done in many places with the Y connection using the ground return where the system is grounded. This has happened in a number of cases where three-phase units are installed and one of the lines has broken down and with a grounded neutral all the rotary apparatus and similar apparatus has gone on operating, and the sub-station man hasn't known that the main line was out until it was reported from outside.

Walter S. Moody: It is pleasant to find Mr. Peck such a thorough convert to the advantages of the three-phase transformer. It is to be regretted, however, that America had to lose so able an engineer before European practice convinced him of the wide range of usefulness of the three-phase transformer.

It was quite natural that American practice with its strong appreciation of the desirability of simplification and standardization of design and construction should for a long time have neglected the saving in cost, simplicity, etc., resulting from the use of three-phase transformers, by using single-phase transformers exclusively. As the volume of transformers manufactured increased, however, the force of these considerations largely disappeared, due to the fact that larger transformer makers had such a large output that the cost of manufacturing a given capacity of both single- and three-phase transformers would not be appreciably greater than making the same capacity of single-phase transformers only. One not acquainted with the facts might conclude from remarks in Mr. Peck's paper that three-phase transformers have been in use in this country but a very short time, and had been produced in very small quantities. While undoubtedly American desire for simplicity and interchangeability retarded more than it should the use of the three-phase transformers, I have strongly advocated their use for six or seven years, and have been responsible for the design and building of some 450,000 kw. ranging in size from five to 7500-kw. units.

Mr. Peck's paper puts the advantages and disadvantages most clearly, in my opinion, and in all important respects, most accurately. There are one or two minor points in connection with the relative advantages of the core- or shell-type construction as applied to three-phase transformers on which I should differ slightly. First, with reference to the ease with which repairs may be made on the core type, I think the European practice of a removable yoke is sufficiently objectionable to offset its advantages. Bolts in a transformer core are always a source of danger, in that the insulation around them may become charred or otherwise damaged, thereby greatly increasing the eddy-current losses. The butt-joint between the yoke and the rest of the core can only be satisfactorily made if the surfaces that are to come in contact are milled or otherwise finished to a true surface. If the surfaces are not finished, or even if they are, the eddy current between the sheets in the two parts of the core may readily be sufficient to cause the welding together of the laminations that Mr. Peck mentions. Some manufacturers use thin sheets of paper between the two parts of the core to avoid this, but the thinnest paper results in a material increase in magnetizing current.

The labor involved in removing the yoke, if it be interleaved with the rest of the structure, is not so great as might be supposed. I have seen such a yoke on a 500-kw. transformer removed and returned to position in fifty minutes. This is certainly not a long time compared with the other necessary operations, including the removal of the transformer from the tank and the exchange of coils.

As one of the disadvantages of the three-phase transformer, Mr. Peck mentions the likelihood of a burn-out in one phase being communicated to adjoining phases. This is quite likely to happen in case of a bad short-circuit in the core-type construction, but I have never known it to happen in the shell type, as the large body of iron between the phases protects the copper in different phases, except the portion that projects beyond the cores, and at these points it is easy to put in a fire-proof barrier. Consequently, the somewhat greater ease with which the core type may be repaired is largely offset by the fact that the damage is likely to be less restricted in its extent than in the shell type.

I agree with Mr. Peck regarding those crosses between a single-phase and a three-phase transformer which consist of two single-phase transformers in one case connected open delta or T.

While the T-connected sets have a limited field of usefulness, because they only admit of returning current to the neutral of the system, yet they are neither single nor three-phase, and like most compromises, are undesirable in many ways.

W. B. Jackson: One point has not been brought out which is certainly an important reason for our not having adopted the three-phase transformer in America. It has not been many years since the operator or the person in charge of an electric transmission plant, in a district where serious and destructive lightning troubles were encountered, held his breath during every lightning storm and he usually has had experiences where one single-phase transformer has gone out of business and the two remaining have saved the day without disturbing his service.

There is a statement in Mr. Peck's paper to the effect that for important work single three-phase transformers are used in Europe. I question whether, for what we would consider important power work, we should be willing, even with the present design of transformers, to use a transformer without some reserve. With the present improved transformer design, we have arrived at a time when the question of reserve is not so important as it was a few years ago, and when it may be policy in some cases to use a single transformer without reserve in cases where the service is not very important. But if we assume a condition where the light and power for a town, a small town if you please, is being supplied from the transformer the service demands a reserve. The same is true of a mining camp, especially so if hoists and mills are being supplied with power, and so it goes with most classes of service. One must have an arrangement by which a portion of the apparatus may be taken out of service and still the service will go on.

We all appreciate the tendency that the prevailing opinion has to change one's ideas on subjects, and I wonder how much the opinion of a person who changes his abode from America to the Continent will change. I remember, five years ago, discussing with a prominent engineer of Austria the relative advantages of using three-phase transformers for transmission work as compared with single-phase transformers. He was unwilling to be convinced that there was a single reason for the use of single-phase as against three-phase transformers until I took up the matter of the lightning conditions as they exist in America. He was then willing to admit that there might be cases where single-phase transformers would work into a power transmission scheme with advantage. The feeling of this engineer seemed fairly to represent the opinions of most European engineers.

P. M. Lincoln: There is one objection to the three-phase transformer that has not yet been brought out. I refer to the matter of leads. In very high voltage transformers, say 60,000 volts and above, it is one of the most difficult elements of the design to bring out the leads properly, and where it is a question of bringing out three leads for 60,000 volts instead of one, as is the case with a grounded neutral Y transformer, or two, as is the case with a single-phase transformer to work in delta, I believe the difference is quite considerable, and that the difficulty of bringing out those three leads in the case of the three-phase transformer as against the one or two leads in the case of the single-phase transformer is a question to be taken carefully into consideration. That objection applies only to the very high voltages. Even with two leads brought out, practically all the available space is taken up by those two leads.

If we have three transformers connected in delta it is possible, as we all know, to go ahead and do business on the two remaining in. However, when that occurs, either there must be an interruption to the service in order to cut out the damaged transformer (if it be damaged) or else we must have automatic apparatus such as reverse-current relays or something of that kind to cut out the damaged piece of apparatus automatically. Now reverse-current relays theoretically can be so constructed as to do that all right, cut out that damaged piece of apparatus and let the other two go on and do business. However, the experience that I have had with reverse-current relays and such apparatus would lead me to be rather doubtful whether in actual practice such a scheme will work satisfactorily. When we get a short-circuit on these high-tension lines, with the tremendous amount of power behind them and synchronous apparatus on the ends of the line, there are surges and other effects going on in that system which we do not know very much about.

C. W. Stone: About bringing out the high-tension leads from very high tension transformers. I think there is a decided difficulty in bringing out the leads of a high-tension transformer. I think there again the three-phase transformer comes in, because we only bring out three leads as against six in three single-phase transformers, and wherever we pass through a case there is a weak point. We have six weak points on three single-phase transformers and only three weak points on the three-phase.

P. M. Lincoln: That applies when the transformers are connected in delta. On the very high tension lines we have the middle of the star grounded and that makes it necessary to bring out only one high-tension lead from each transformer. The other lead can be connected right to the case inside.

C. W. Stone: I meant to confine my remark to the delta connection.

Edward A. Wagner: It seems to be the concensus of opinion that the three-phase transformer is the proper thing, based I believe on the assumption that the secondary load is three-phase distribution to a three-phase motor. In this country the practice of a good many stations is to have three-phase generators, and distribute mixed loads; that is, motors and light; and where they distribute for light the distribution is frequently scattered so that it would not pay to put in a three-phase transformer to furnish the light. In such cases the single-phase transformer is far more desirable, because the extra copper required for running the secondary lines would more than offset the advantages of the three-phase transformer. I think, then, that in taking up the question of preference of three phase over single phase, it is acknowledged that the three-phase transformer is more efficient than three single-phase transformers combined, but there are other cases where the condition of operation may possibly determine the necessity of installing single-phase transformers.

A. H. Pikler: Mr. Moody says that the disadvantage of the core-type transformers with butt-joints is that the insulation around the bolts might get damaged. That may be so, but not if the transformer is properly made.

As to the increase of eddy currents due to the milling of the adjoining surfaces. The decreasing of the eddy currents is done, not by interposing a sheet of paper between the yoke and between the legs, as Mr. Moody suggests, but by interposing paper between the sheets of the yoke, or between those of the leg. As to the increase of the magnetizing current, it seems to me that the magnetizing current in a shell-type transformer, other things being equal, is a good deal higher than in a core-type transformer where the surfaces are carefully milled, because the magnetic reluctance in a shell-type transformer on account of the flux, the lines of force, traveling from one plate to the one above, and so on, or from one plate to the adjoining plate in the same plane through an air-gap, is much greater than in a core-type transformer with butt-joints. It seems to me that the core-type transformer with the butt-joints is a great advantage to the customer, because it enables him to repair a transformer in a very short time. For instance, such a transformer even above 400 or 500 kw., if a coil is damaged, may be repaired in four or five hours, whereas in a shell-type transformer one has to pull out every single sheet of the core, then take the coils out, repair the coil, and then build up again the core by single sheets. This causes great delay in repairing. It takes probably two or three days, and with large units repairs cannot be made at the station at all; the units have to be returned to the factory. Whether it is butt-joint or not, I believe that the proper construction for a high-tension transformer is the core type, because in a core-type transformer one can separate very easily and conveniently, either by insulation or by oil ducts, the high- and low-tension windings, whereas in shell-type transformers, both the high and low-tension coils necessarily must be supported by one support, and on that support the creeping surface cannot be made large enough to allow a good insulation. It is necessary to put very heavy insulation between the coils and core, between or over the high-tension and low-tension coils. The disadvantage of this is that, if there is good insulation, there is retained within the coil also the heat which cannot radiate, whereas between the high- and low-tension coils in a core-type transformer there is always circulation through the open duct around the coils. This is not the case with the shell-type transformer. In the shell-type transformer coil there are quite sharp corners on the top and bottom of the coil and at the same point there is the support of the coils. From this it can be seen that at the very point where the construction is mechanically the weakest, it is also weakest electrically, and it is also weak from the point of heating.

E. N. Lake: Irrespective of minute details of manufacture, I think we would probably all agree upon the use of three-phase transformers if we confined that use to distributing systems consisting of a large number of sub-stations interconnected by means of underground circuits. But in the matter of the use of these transformers for interurban railway conditions in which there is a string of sub-stations, any one of which is quite essential to the operation of the road, the danger of interruption to the service would be materially greater in the case of a three-phase transformer than with three single-phase transformers. I have in mind a road some 35 or 36 miles in length, which depends for its operation upon three sub-stations. These sub-stations are equipped with three single-phase transformers, each operating a single converter. One spare transformer was provided, making a total of ten transformers for the system. During light'ning or other disturbances upon the system, when some of these transformers went out, it was possible to operate with only 60% of the transformer equipment in service; that is to say, with four out of the ten transformers out of service, the road could still operate. I think that those who are interested in the operation of such roads, where there are not the advantages of the interconnected system and not the protection against lightning of the underground distribution, will hesitate to recommend the three-phase transformers.

H. B. Gear: With regard to the use of three-phase transformers for pole work suggested by Mr. Stone, in view of the possibility of using the open delta system for such installations, the use of small three-phase transformers does not seem to be especially advantageous. The saving thus made by the use of two single-phase transformers instead of three is about equivalent to the saving made in manufacturing cost by installing three cores in one case. Furthermore, so far at least as one company is concerned, the prices quoted for the three-phase units thus far show no saving whatever over the cost of three single-phase units.

As to the larger units, say over 25 horse-power, where it is customary to use three one-phase transformers, where they are mounted on a pole the disposition of the weight is rather more easily effected where there are three single units than with one unit. A 60- or 75- or 90-kw. unit, which would be required for a good many three-phase installations in Chicago, is a very awkward thing as a single unit to set on a pole, unless a platform of some sort be set to one side, or a separate pole set and a platform put between them, whereas three 20- or 30-kilowatt units can be installed on ordinary hangers by using double arms of a little extra strength, without any platform construction and at less expense of erection.

As to the use of underground three-phase units, the advantages cited by Mr. Stone are undoubted in that the number of joints in the manhole is reduced, but there is the quite material disadvantage that a three-phase unit of 60 or 75 kw. is so large that special manhole covers must be provided to get the apparatus in and out of the manhole, whereas, with the single-phase units, either of them which may be damaged can be taken in or out through an ordinary size manhole cover.

Perhaps the most serious objection, however, to the use of three-phase units in a large distributing system is the fact that a full equipment of another type of apparatus must be carried in stock. To a company which is installing and removing every day a considerable number of transformers for both lighting and power purposes, the question of keeping a full quota of all sizes in stock is a matter of great importance. Most central stations have, therefore, found it preferable to use the same kind of transformers for both lighting and power, as they can thus carry a line of three or four of each size in stock and are prepared for any three-phase power installation or for any lighting installation at any time.

A. H. Pikler: I notice that the matter of regulation has not been taken up at all in the comparison between single-phase and three-phase transformers. The regulation of a single-phase transformer is better than that of a three-phase transformer. The regulation depends, especially in the case of power transformers, where the load has a power-factor less than unity, mostly upon the reactance of the transformer. In a core-type transformer the reactance depends upon the length of the leg over which the coils are distributed, the relative distance between the coils, and finally the thickness of the coils. In a shell-type transformer it depends on the dimensions of the coils and the number of subdivisions between the primary and the secondary coils. If we make three single-phase transformers into one three-phase transformer, then, in a core type, we have to use a shorter core and thicker coils, consequently the reactance of the transformer will be greater. In a shell type when combining three single-phase transformers into one three-phase transformer, we have to crowd the coils together, and make them thicker, allowing less intermingling between primary and secondary coils, else the magnetic circuit will grow too big, the weight of iron too great, and the magnetizing current excessive. So from this we can see that the reactance in both cases is greater and the regulation of three-phase transformers compared with single-phase is worse.

Edward A. Wagner: I do not agree with Mr. Pikler on that score. The combining of three single-phase transformers into one common unit or on one common magnetic circuit does not affect the reactance of those coils, because the reactance of the coils due to the leakage in the iron is negligible. The internal reactance of the coils is proportional to the area of the path between primary and secondary and inversely as the length. Combining them on a magnetic structure so as to get a multiphase magnetic path does not affect the reactance of each separate coil, and it should not, therefore, affect the regulation, since the regulation is due entirely to the combination of the resistance and the reactance of both primary and secondary coils.

A. H. Pikler: I did not say that the combined flux affects the primary and secondary coils of the reactance at all. I took one single-phase transformer alone and one three-phase transformer alone, a single-phase transformer of one-third of the capacity of the three-phase and the three-phase transformer the aggregate capacity of three single-phase transformers. If you know what are the factors in determining the reactance of a transformer, it is obvious that in a single-phase transformer those factors are more favorable for a smaller reactance than in a three-phase transformer. The combined flux has absolutely nothing to do with it.

Edward A. Wagner: As I understand Mr. Pikler, his comparison is on the basis of, say, 300 kw. capacity. He makes the statement that if we have a 300-kw. three-phase transformer, and on the other hand three 100-kw. single-phase transformers, that the single-phase transformers connected delta or **Y**, whichever way he pleases, will give better regulation than the 300 kw., three-phase transformer. Now the only difference between the three single-phase transformers and the one three-phase transformer is that the three-phase transformer has the same number of coils combined on a smaller core, and since the core-loss is proportional to the weight, we gain greater efficiency in total output. But as far as reactance of the coils and the resistance and the weight of copper in the outfit, there is no difference between the three single-phase transformers and the one three phase transformer, because the reactance of the coils is the same in either case.

A. S. McAllister (by letter): Mr. Peck says:

> On account of the phase relations of the currents, the capacity of each (V-connected or T-connected) transformer must be 15 per cent. greater than half the capacity of the three-phase transformer, with a corresponding increase in cost and losses. There is another serious objection to this (either the T or V) arrangement, for on account of the out-of-phase relation of voltage and current the voltage across the three phases will not remain balanced as the load comes on.

The author's remarks are true when applied to the V-connection, but they must be somewhat modified when dealing with the T-connection. When two transformers are T-connected on both their primary and secondary sides, one of the transformers must be designed for 15.5 per cent. more volt-amperes than one-half the rating of the equivalent three-phase transformer, but the other transformer is subjected to exactly one-half of the volt-amperes of the three-phase transformer. If the voltage between the phase leads is E, and the current per lead I, the three-phase transformer must be designed for 1.732 $I\,E$; one of the T-connected transformers would be designed for $I\,E$ and the other for 0.866 $E\,I$.

Two transformers with T-connected primaries and secondaries will transform three-phase power from one voltage to another without voltage distortion equally as well as will two similar transformers used to change power from two-phase to three-phase; even for unbalanced loads the transformation will be satisfactory, provided only that the transformer with the larger volt-ampere rating be constructed with its primary and secondary coils well interspaced.

W. F. Lamme (by letter): The strongest argument against using three-phase instead of single-phase transformers is the one of accident to the transformer, but when the installation of transformers becomes very large so that the number of reserve transformers becomes large this argument of accident decreases.

Transformers as built to-day by responsible manufacturers are quite reliable, and the chances of breakdowns are, or can be made, remote. In the case of three-phase transformers this reliability can be increased by the use of more careful design and construction and higher insulation tests, and the customer can still get his three-phase transformer at less than three single-phase transformers will cost him, and the risk of a shutdown in the two cases due to accident to the transformer may be considered as equal.

K. C. Randall (by letter): For quite small units up to approximately 100 kw., or even larger, where interruption may be tolerated, the three-phase unit will doubtless show up well. Where the units are larger and isolated, and especially where continuity of operation is of prime importance, three single-phase units will probably show better in three-phase work. As sizes of 1000 kw. and larger are approached, the three-phase units again come to the front, especially as to installation costs.

As to handling when the station is new, during the course of construction provisions may be made for lifting nearly any size unit which it may seem desirable to install; therefore, the choice of the single-phase unit is not necessarily an essential consideration. If a large growth of power business is contemplated, and if at first it is desirable to install but one or two of the future six or eight units, it may be advisable to use the three-phase units irrespective of their size.

If the station be an old one, it will probably be desirable to adhere to the already selected type of unit, unless the original choice has been subject to improvements, which would warrant the selection of different units. This would mean two different types within the same station, or upon the same system, and probably sacrifice the interchangeable feature.

The failure of a three-phase transformer or of one of a group of single-phase transformers is about of equal significance in its bearing upon a shutdown. In either case, if operation is delta-delta, switches may be so arranged that the transformer on the faulty phase may be cut out, the remaining two transformers operating in V to carry a portion of the load. This applies equally well to the single-phase or three-phase units. Shell-type transformers are here contemplated. A failure in any phase of a core-type will put the transformer out of service, unless the faulty phase can be opened and isolated. If operation were star on either end, then operation could not be continued until the unit was repaired or replaced. The cost of the three single-phase units with a spare unit may be called 400%; and the cost of two equivalent three-phase units 500%. The cost of two groups of single-phase units; that is, six transformers, will be 600%. As a matter of fact, it is doubtful if the two three-phase units will actually cost any more than the four single-phase units when they are finally installed, wired up, water-piping completed, and ready for operation, the single-phase units being arranged so that any three may operate in a bank, and the three-phase units being arranged to operate singly or in parallel, as may be desirable. It should not be lost sight of that the three-phase units have a capacity of 200%, while the three single-phase units have a capacity of but 100%, it being impracticable to use the fourth transformer to advantage with the delta-connected group. However, the four transformers may be connected in open delta, two on each leg, so that a capacity of 13% higher with the same heating effect in the transformers, is obtained. The gain in capacity is in general obtained at the expense of regulation, it being well known that transformers, operating in " V " or open delta, do not give equal regulation on the three legs of the three-phase circuit.

It would then appear that for good size units, say 1500 to 2000 kw., in stations where considerable power is to be used and a continual growth of business is expected, it will frequently be advisable to employ three-phase units rather than single-phase, as in this way complete new units may be installed one at a time to much better advantage than if single-phase units were used in groups of three. The three-phase unit being the heaviest, it will generally be more difficult to handle, particularly in the case of old stations where crane facilities are very limited; yet it still may seem advisable to install the three-phase unit, making a special effort for this purpose. Side tracks are now generally found near stations, so that the transportation matter is pretty well taken care of.

There is a tendency to ship transformers unassembled, as is done with large generators. If this is done the disadvantage of the additional weight of three-phase over single-phase units is small, and it will only require the attention of an experienced man for a number of days to put together the three-phase units on the premises rather than at the manufacturer's works.

D. L. Huntington (by letter): For nearly four years the company with which I am connected has been purchasing three-phase transformers for nearly every installation of 150 kw. or more, and is using transformers of this kind in sizes from 150 kw. to 2200 kw. These transformers have been installed on 60,000-volt lines, star-connected with grounded neutral. Under these circumstances there would be practically no advantage in case of breakdown by the use of three one-phase transformers, as the latter could not be used to obtain temporary service.

On all remaining points the three-phase transformer has a distinct advantage; namely, first cost, convenience, simplicity of wiring, space occupied, piping and general expense of drying out, filling with oil, and installing. If the large quantities of oil used in transformers be considered a serious fire-risk, the one-phase installation will be much more of a risk than the three-phase on account of the larger quantity of oil required.

Mr. Peck says that with the core-type one- or three-phase transformers there is much less need of providing spare capacity than if the shell type is used. I wish that our experience would bear out this conclusion; but unfortunately we have had all our transformer troubles with core type and none with shell type. I will of course admit that in case of a burn-out the core type is much more readily repaired; but in that very fact lies the reason of its inferiority as against trouble, for the looseness of construction, which so readily admits of the removal of coils is the cause of most of its failures, so far as our experience goes.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907.

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FORCED-OIL AND FORCED-WATER CIRCULATION FOR COOLING OIL-INSULATED TRANSFORMERS

BY C. C. CHESNEY

With the increased demand for large individual transformers, and for installations of large aggregate capacity, the relative merits of forced-oil and forced-water circulation for the cooling of oil-insulated transformers have been recently receiving the special attention of transformer designers.

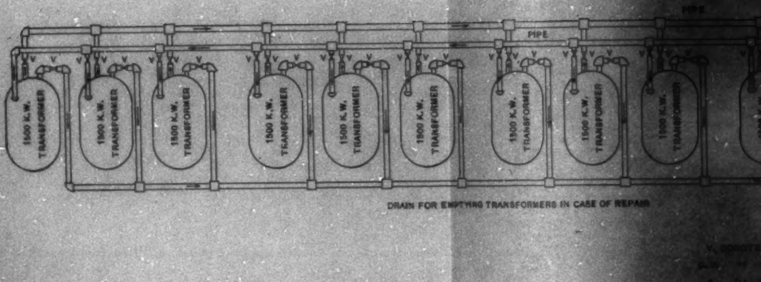
The method of cooling transformers by means of forced-water circulation has been in use a number of years, and is too well known to require any more than a very general description. The essential feature is a cooling coil of pipe composed of a number of turns of iron, brass, or copper pipe placed in the oil in the upper part of the containing tank, and generally above and around the ends of the transformer windings. Through this coil is circulated the necessary cooling water, the heat being transferred from the winding and core to the pipe-coils by the natural circulation of the oil from the heated parts of the transformer to the cooler pipe-coil.

The more recent methods of cooling transformers by forced-oil circulation does away entirely with any internal cooling coils, but makes necessary external auxiliary cooling apparatus. The lower part of the windings of the transformer is enclosed in a metal box containing suitable directing plates, and this box is connected to the oil inlet by a vertical pipe raised to the top of the tank and passing through the cover. The outlet pipe has its opening somewhat above the top of the windings, thereby insuring a safe oil level. Oil under a slight pressure is introduced through the inlet pipe, and in passing through the transformer the oil is brought into intimate contact with the various windings and laminations by means of ducts and directing plates. After leaving the transformer, the oil flows through an external cooling system containing a surface condenser and strainer, and an oil pump, the latter providing the pressure needed to keep the oil moving at a proper rate through the entire system. An additional pump is provided to circulate water through the condenser. Sufficient water is usually circulated through the condenser to give a 10° cent. rise to the water temperature, and the rate of oil-flow is usually adjusted to approximately twice that of the water. The organization of the entire cooling system is shown in Fig. 1.

To offset the additional cost which this auxiliary cooling apparatus represents, there is a less first cost of the transformer proper, due to the markedly more efficient cooling which the positive circulation of the oil insures, and to the prevention of any local heating, in pockets, etc. The density in both copper and iron can be increased for the same temperature rise, which means less material used in the design of the transformer. In addition, since there is no cooling coil, the tank can be reduced in height, and less oil will be needed to fill it.

The total saving in the transformer proper will vary from 15 to 25%, depending upon the size of the transformer. The reduced height of the transformer is, however, particularly welcomed on the score of shipment. With forced-water circulation the designer is handicapped, in the larger sizes, by being limited to a height of approximately 11 feet; this being the maximum height that can be safely shipped on any of the American railroads. By the use of forced-oil apparatus, however, the capacity of the transformer which can be shipped completely assembled is materially increased. On the other hand, as against the gain in head-room the total floor space required will be greater, on account of the additional floor space required for the auxiliary cooling apparatus.

If a comparison of the total cost of the transformers installed is taken, the balance in favor of the forced-oil system appears for the large installations of 4000 to 5000 kw. when composed of individual transformer units of not less than 1200 to 1500 kw. While forced-oil circulation is undoubtedly out of the qestion for smaller plants and smaller units, it merits for the large power plants the most careful consideration of any engineer.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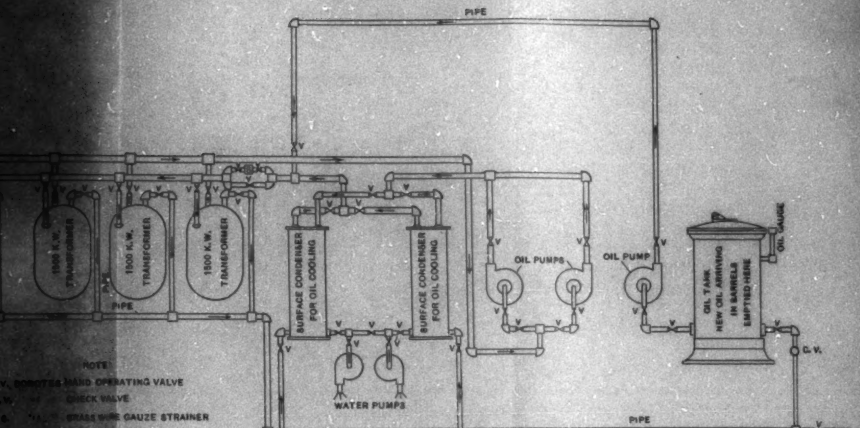
FORCED-OIL CIRCULATION FOR COOLING OIL-INSULATED TRANSFORM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SURFACE CONDENSER FOR OIL COOLING
SURFACE CONDENSER FOR OIL COOLING
WATER PUMPS
OIL PUMPS
OIL PUMP
OIL TANK NEW OIL ARRIVING IN BARRELS EMPTIED HERE
OIL GAUGE
C. V.
PIPE
DRAIN TO TANK OR SUMP OUTSIDE OF BUILDING FOR DAMAGED OIL
NOTE:
V. DENOTES HAND OPERATING VALVE
C.V. " CHECK VALVE
S. " BRASS WIRE GAUZE STRAINER

SFORMERS

FIG. 1

DISCUSSION ON "FORCED-OIL AND FORCED-WATER CIRCULATION FOR COOLING OIL-INSULATED TRANSFORMERS," AT CHICAGO, MAY 24, 1907

C. W. Stone: Mr. Chesney points out one thing that should be considered in two ways; the extra floor space required. It is true that if one considers the space taken by the condenser outfit for cooling the oil and the extra pumping apparatus necessary, more floor space may be required, but that extra floor space can usually be found in most stations. The space necessary for the cooling apparatus, the pump and condenser, is not so great as the space occupied by the transformer, and they can usually be put away in some corner in the station. Also in several cases I have found it advisable to install this cooling coil, not in a part of the station but, say, in the tail-race, using the water from the turbine to do the cooling. There is not, therefore, the complication of extra pumping facilities; there would be one set of pumps similar to those that are ordinarily used for forced water circulation in a water-cooled transformer.

Another important thing to consider in connection with the forced oil-cooling of transformers is head-room. Most of the attention given in this paper is on the score of shipment. This is a serious matter only in the very largest size; but frequently in the design of a water-power station where the station is built right on the rock, considerable excavating is necessary in order to provide transformer compartments; and where the rock is solid, the expense is considerable, and if one can dispense with any head room at all it is well worth saving, even if it is necessary to incur the expense of extra pumping facilities.

It is also true that the oil is under moderate pressure; therefore very little trouble should be experienced from the pumping outfit with forced oil circulation and separate cooling. That is, the troubles experienced are not nearly as serious as in most central stations where the oil has to be pumped anyway, and frequently at much higher pressure. An ordinary small, low-pressure, motor-driven pump is about as simple a device as can be put in a station.

W. S. Moody: One little detail that Mr. Stone did not speak of in connection with forced-oil designs is perhaps worth mentioning; namely, the incidental advantage attained when it is possible to locate the cooler in the tail-race of a generating station. Here, having practically an infinite quantity of water compared with what is actually needed for the cooling, there is no perceptible rise in temperature of the water.

When the water for cooling is pumped through the cooler it is hardly ever practicable to use a larger quantity of water than that which will be raised about 10 degrees in temperature; consequently the average temperature of the cooling water, when the cooler is in the tail-race, can be considered as five degrees less than when water is pumped through the cooler, The result is either a reduction of five degrees in the actual temperature of the transformer under full load, or the possibility of using a cheaper transformer having the same actual temperature as one cooled by artificially circulated water.

A. Henry Pikler: The idea of cooling transformers in this way is not recent. The reason for the increasing use of this method of cooling is due to the development of very large units, which require special devices for keeping the temperature within the proper limits.

The dissipation of heat in transformers with forced oil circulation is primarily due to convection and not to conduction or radiation. Consequently the speed with which the oil is forced through is of vital importance; the greater the speed up to a certain limit, the better the cooling and therefore the smaller the apparatus for a certain given rise in temperature. Therefore the statement: "The total saving in the transformer proper will vary from 15 to 25% depending upon the size of the transformer," has very little value unless the speed be given.

As in all apparatus which has forced cooling, so with this one—the danger arises in the case of breakdown of the cooling arrangement. The density in the copper and the iron, and consequently the heat generated, is higher in this than in transformers cooled by other means. If the cooling arrangement gets out of order, the former kind of transformer can be operated without forced cooling for fewer hours than the latter; this is certainly a disadvantage in the former system.

W. B. Jackson: There seems to be one advantage here which has not been pointed out. In this system of water cooling transformers the possibilities of trouble from leaking water pipes may be entirely eliminated; in other words, instead of there being pressure tending to force the water into the oil it is entirely practicable so to arrange the system that the water will be drawn through the cooling coils in such a way that the old danger of water getting into the oil and in that way short-circuiting the transformers, is entirely overcome.

W. S. Moody: I was just referring to this particular possibility of trouble. As soon as the idea of using the forced-oil method of cooling occurred to us, this source of danger naturally presented itself as something necessary to guard against. We do so by simply arranging that the water and oil pressures in the cooler be such that the leakage will be in the direction from the oil to the water, so that if there is any little leak the result is simply a little loss in oil. There is no possibility of water leaking in the other direction.

P. M. Lincoln: There is one disadvantage that occurs to me and one which no one has yet mentioned, and one which the oil transformer designer realizes more than anything else; namely, that oil is the hardest stuff there is to keep where it belongs; and the more piping, etc. there is to convey this oil around the more danger there is of getting leaks and a condition which might be best designated by the term "sloppy". That is, I think, one real objection to the scheme of having forced oil circulation rather than the present. It is undoubtedly cheaper; that is to say, there are bound to be less materials used with a properly designed oil circulation than if the oil is allowed to circulate itself, and efficiency can be improved for the reason that with a more efficient means of carrying off the heat there is bound to be an improvement in efficiency. As against that there is this condition of having a greater tendency to leakage and having an auxiliary apparatus which the modern operator, if my experience leads me to judge aright, tends to avoid rather than to court.

S. M. Kintner (by letter): Mr. Chesney treats only briefly a subject about which a great many interesting things can be said. In his brevity he has left at least one point that needs to be qualified. He says: "The density of both copper and iron can be increased for the same temperature, etc." The above is true for the higher frequencies only so far as change in density in the iron is concerned. It is not the loss and consequent temperature in the iron that prevents a greater magnetic density for the lower frequencies, but it is the increased magnetizing currents that would follow working at any greater magnetic intensity.

There are several characteristics of oil that must be borne in mind for a thorough appreciation of the various methods employed in cooling oil-insulated transformers.

The oil is an extremely poor conductor of heat. I have repeatedly noted temperature differences of 60° cent. in a column of oil only 6 in. tall. The heat was of course applied at the top of the oil column. The above condition is one that existed after several hours' operation so as to insure a final balance of temperature conditions.

The oil carries heat by convection currents only and consequently has a tendency to pass upward only. This makes it extremely important to see to it that no dead oil pockets exist in the transformer, as otherwise a hot spot of 50 degrees or 60 degrees cent. excess might exist locally in the windings.

The oil film heated by contact with the hot coil tends to rise along that face. This oil film is very thin and exceedingly difficult to measure. Temperature measurements taken by thermometer laid alongside of the coil face will give an incorrect reading, unless specially guarded against the oil flow. Temperature differences of five or six degrees have been noted within one-eighth of an inch of the coil face when explored with a point thermo-couple.

Oil acts simply as a heat ferry in taking the heat from the inside of the transformer to the place where it can deliver this excess heat to a dissipating body. It is, therefore, evident that large "docking facilities" are very essential in order to prevent congestion of traffic of the little heat ferries; that is to say, ample contact area between the oil and the source of heat and again between the oil and the dissipating body is required.

All the above points should be given thorough consideration in the development of the various systems of transformer cooling. The following brief discussion gives the principal points involved in the best known methods of cooling.

Self-cooling, oil-insulated transformers. Self-cooling transformers give up their heat to the surrounding air and the improvements in these, in so far as cooling is concerned, have been improving the facilities of the oil for loading and unloading the heat. The unloading facilities have been improved by using corrugated cases, by using cast iron ribs and pins, by using larger tanks (particularly taller ones as the top of a transformer tank is by far the most effective radiator to the air on account of its higher temperature above air) and lastly by using tubes, containing a certain proportion of volatile liquids that will vaporize on being heated slightly, and consequently keep the tubes at almost uniform temperature throughout their entire length.

All of the above devices have sought to get more contact area of heated air with tank or body which is to deliver the heat to the air, and to get more oil contact surface with the tank or as equivalent.

Forced water-cooled transformers. As the speed with which the oil moves is directly dependent upon the temperature difference of the oil, it is evident that more rapid oil movements will be obtained in the water-cooled transformer with its chilling water coils near the top of the tank than in the self-cooler. The increase in oil speed is a very desirable thing, as it sweeps out the oil vent ducts in the transformer and keeps them supplied with fresh cold oil. The speed of oil movement is dependent upon the temperature difference between the hot oil and the cold oil in which it is immersed. This speed can never exceed a certain maximum because of permissible temperature differences being limited to fairly small values, possibly not more than 20 degrees cent. should be allowed. It is evident therefore, that this method of cooling reaches its limits from the lack of sufficient speed of oil movement.

There have been some instances of cooling in which the transformer tank was immersed in running water. This is but a modification of the above method and has given satisfactory service in a number of places.

Care must be exercised in using these methods to prevent leaks of water into the oil, as a trifling amount of water will cause serious damage.

Moisture will sometimes condense on the surface of the water-cooling pipes at the points where they enter the transformer; this is caused by their temperature being lower than that of the surrounding air and is readily prevented by lagging the pipe so as to prevent its coming in contact with the air inside the transformer tank.

Frequent inspection of the water coils is necessary to make sure they are not collecting sediment on the inside that would prevent water flow.

Forced-oil circulation transformer cooling. This method, which involves the drawing off the hot oil from the top of the transformer tank and the cooling of the oil before it is returned, has its principal advantage in the increased rate of oil movement that is possible.

It has an additional advantage in that the cold oil can be delivered directly in the transformer against the copper and iron.

It is possible with this method of cooling to increase the rating of the transformers from 15 to 30 per cent., depending upon conditions involved in individual cases. A fairly accurate idea can be obtained of the amount of cooling possible with this method if the figure 9 gallon-degree-min. per kilowatt is taken. From 25 to 30 degrees of cooling is possible if sufficient radiator capacity can be obtained. There is no difficulty in getting this if the radiators are immersed in cool running water.

Fig. 1.

Figs. 1, 2, and 3 illustrate an installation of the above kind at DeCew Falls, near St. Catherines, Ontario. In this plant, five 2500-kw. oil-insulated transformers are each provided with a forced-oil cooling system. In this installation each transformer has an independent cooling system which is in no way connected to the others save in the source of electric supply of the individual motors.

Rotary pumps driven by induction motors, all arranged on the same sub-base as shown in Fig. 1, circulate the oil at the rate of approximately 90 gallons per minute. The oil is drawn from the top of the tank by a pipe which enters the tank through the cover and dips down into the oil to a depth of approximately eight inches below the surface. The oil after passing through the pump passes to the cooling coils. Fig. 2 is a view of one of the coils taken as it was being lowered into position in the tail-race of the plant. The oil, after passing through this coil where its temperature is lowered to within a few degrees of that of the water, is delivered directly against the bottom of the copper coils of the transformer. The bottom of the transformer is partly closed so as to force the large part of the cold oil to pass upward through the transformers. The rest of the oil passes up around the outside of the iron and assists in carrying away the heat due to the iron loss.

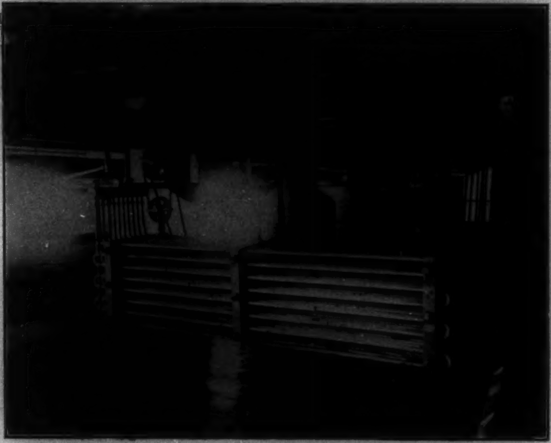

FIG. 2.

A check-valve is placed in the pipe at the inlet to provide against possible danger of draining all the oil in the event of the cooling coils being torn away by ice or drift in the tail-race.

The pressure of the oil is always in excess of that of the water, and consequently a leak would cause a loss of oil but no inflow of water. A very small oil leak is readily noticeable in the water, so that the system seems amply safeguarded both as regards safety of operation of the transformers and against loss of oil.

Fig. 3 shows several of the cooling coils in position. This view was taken at a low-water period during the time of erection.

These cooling coils have been in service about a year and a half and have given very good service. No trouble has been experienced with leaks in the coils or with troubles from driftwood or ice. No difficulty has been experienced in starting the cold oil after standing idle for hours in the low temperatures that exist in Canada.

Fig. 3.

It is possible to use a single pump for installations of this kind in place of the more expensive arrangement shown in the views above, provided this pump draws its hot oil from a common tank which fills from overflow outlets in the various transformers. An arrangement of this kind makes a safe operating condition though hardly as satisfactory as the individual pumps.

There are some places, where water is not available, where the circulation of the oil through radiators which dissipate their heat to the air will be found the best available. This air cooling can be assisted by fans directed against the radiators.

A. H. Babcock (by letter): Some expensive experiences with cracked or punctured water coils in high-potential transformers caused me, several years ago, to discuss with the manufacturers, the oil-circulation cooling method. At that time there had not been reported sufficient troubles of this kind to make the matter of enough importance to force the factories away from a manufacturing standard method.

In making the installation, it is suggested that in addition to the reversed connection of the water circulating pumps, as shown in the author's sketch, the condensers be placed in such position relative to the oil piping that, with all pumps stopped, the oil pipes in the condensers will be under a static head. Under no conditions should it be possible for the water to rise into the oil-circulating pipes.

To avoid condensation within the transformer case, the oil should not be cooled below the temperature of the air in the case. A pair of thermometers, one in the air of the transformer case, the other in the oil, provided with contacts within their bores, and connected bridge fashion, could be used to give an alarm when the temperature of the oil falls too low. Similar thermometers with a single pair of contacts have been used on the Pacific coast for several years, to signal excessive oil temperatures.

It is suggested further that a system of air cooling the oil be developed for use in arid regions where water is difficult to obtain.

Broadly considered, in my opinion the disadvantages named by the author are of small importance compared with the obvious advantages.

M. C. Canfield (by letter): It seems to me that some of the advantages incidental to the forced-oil circulation system have been overlooked in the paper under discussion. In the forced-water circulation type, there is occasionally trouble from sweating of the water pipes at the top of the transformer case, and many transformers are built with heat-insulating coatings on the upper portion of the cooling pipes where they are above the oil. This sweating is, of course, due to the great difference of temperature between the air in the top of the transformer case and the water pipes. This difficulty does not occur in the forced-oil circulation system.

Any leakage which may occur in the cooling coils of a water-circulation transformer, results in the escape of water into the transformer case, and consequently, into the oil. In the case of the forced-oil circulation it is a simple matter to keep the oil at a higher pressure than the water, so that any leakage which may occur will be a leakage of oil into the water, and not vice versa.

Mr. Chesney refers to the possible reduction in height of transformer obtained by the use of forced-oil circulation, but suggests that the total floor space required will be increased because of the space required for the cooling apparatus.

In the case of the transformer with forced-water circulation, the transformer-case must be of a size to contain the transformer, and to provide ample space around it for the circulation of the cooling oil. This space must be large, to provide for the descending currents of cooled oil, and as the pressures acting to produce such currents are very small, being due to differences in specific gravity of the oil only, the currents are slow and require much space.

In the case of the forced-oil circulation the situation is completely altered, as it is only necessary to provide for the flow of oil in one direction within the transformer, the flow in the opposite direction taking place through the piping of the cooling system. It is desirable to make the transformer case fit quite closely around the transformer, in order to throw the oil current against the transformer as much as possible. It would therefore seem possible materially to reduce the floor space occupied by a transformer equipped for forced oil-circulation. This reduction of floor space should materially offset the space occupied by the auxiliary cooling apparatus, especially with large installations.

G. Percy Cole (by letter): Occasions may arise in very large installations where it would certainly be good engineering to adopt transformers cooled by forced-oil circulation, but, taking everything into consideration, these instances are exceedingly rare, and it will usually be found that the water-cooled type will fulfil the requirements satisfactorily in spite of its slightly increased size.

The water-cooled type appeals more favorably to engineers for the following reasons:

1. Because it has passed the experimental stage, and proved its reliability, even in the very largest units at present installed.

2. The simplicity of the cooling system. The majority of power houses, where very large units are installed, are hydroelectric, and in such cases the water required for cooling costs next to nothing; the piping being reduced to a minimum, since a gravity system will replace pumps in a great many cases.

3. Less liability for the oil to take up moisture. We hear of extremely few instances where trouble has resulted from cooling coils leaking. The adoption of cooling coils of seamless copper tubing, and the great care bestowed by manufacturers in building and installing this tubing have resulted in almost absolute freedom from the trouble of water getting into the oil from the cooling system.

With the adoption of very large units and high voltages (60,000 to 80,000 volts) it is absolutely necessary that the oil surrounding the coils be kept free from moisture. Where oil has to be circulated through the transformer, out through piping, through large cooling systems and pumps external to the transformer, there is much greater danger of getting water into the oil than with water-cooled transformers. Even if a gravity water-cooled system cannot be employed, and pumps have to be used, water circulation shows up more favorably even if only taking into account the amount of liquid circulated; for since oil has a specific heat of approximately half that of water, it is quite evident that at least twice the number of gallons per minute for the same cooling effect would have to be circulated if oil circulation were adopted than if water-cooled had been used instead.

D. L. Huntington (by letter): The advantages which forced oil would have over forced water appear to me as follows:

1. The movement of the oil, being guided specially to those portions of the windings or core which most need cooling, should be much more effective than with forced water, and for this reason higher efficiencies and longer life should be had for a given combination of copper and iron; or the equivalent of a larger output with the same efficiency and life.

2. In large or comparatively large installations there would probably be a saving in first cost; but on small installations this is very doubtful.

3. Where clean water is not obtainable for forced-water transformer coils the gradual clogging up of the coils is inevitable, and I know of no effective means of cleaning them thoroughly. Under such conditions the forced oil method becomes almost necessary where the installation is to consist of large units otherwise the use of smaller units of the self-cooled type would be the only practical resource, and that a very expensive one, not only in the transformers, but in the buildings and wiring.

4. In case the forced-water type of cooling coils are used which enter and leave the top of the transformer, there is danger of freezing if the transformer is temporarily out of use, and the only practical plan which we have been able to find is to blow the coils out with compressed air. The forced-oil system would be easy to drain of water on such occasions. This advantage would not apply to those forced-water transformers with bottom inlet and outlets, upon which I have for some time insisted, and which are of course readily drained.

Disadvantages

1. For the forced-oil system some measure of attendance, comparatively regular and frequent, would be absolutely necessary. This would mean a greatly added expense in many plants, such as our's for instance, where we have numerous sub-stations of from 150 to 1500 kw. capacity in a mining country, where the only attendance now required is for a few minutes once a day.

2. With forced-water transformers it is usually possible to obtain water of steady flow and under the required pressure at small expense, and the cooling is therefore very simple, and consequently, very reliable. The forced-oil system is much more complicated and cumbersome and much more likely to get out of order, and, to assure reliability equal to the forced-water system, a considerable part of the circulating apparatus should be in duplicate.

3. My experience is that in case of a burn-out in a high-tension transformer the oil usually becomes so carbonized as to be unfit to use again until it has been carefully filtered. In such a plan as that shown in Mr. Chesney's paper, the pumps would immediately distribute this carbonized oil to all the uninjured transformers, a really serious matter. A similar effect would be had if a water leak developed. As an insulator, all the oil would, to some extent, deteriorate, and would all have to be dried With the other system the oil of one transformer only would probably have to be treated.

4. To remove these objections to some extent, forced-oil coolers could be installed for groups of transformers. This only lessens the objection, however, and adds materially to first cost and operating cost.

5. Furthermore, if any moisture is carried into the oil in the forced-oil plan, the oil carries it to the plates in the transformer where it will be most likely to do harm, whereas moisture may accumulate in appreciable quantity in the bottom of a forced-water transformer without doing damage.

Generally speaking, unless the objections regarding spreading of damaged oil through the undamaged transformers can be overcome in some simpler manner than by having a separate cooling plant for each unit, I think the advantages of the forced-oil system are distinctly over-shadowed by its disadvantages. Perhaps some ingenious and simple method may be devised to shut off the oil circulation automatically from a damaged transformer. Then, in that case, there are many installations where the size is of some moment, in which the forced oil cooling will be distinctly the best to adopt.

W. F. Lamme (by letter): There are certain cases in which it is better to cool the oil in the transformer through circulating oil through cooling coils in water than by circulating water through cooling coils in oil. In a water power plant an abundance of cool water is always at hand for cooling purposes, and there seems no good reason why these cooling facilities should not be taken full advantage of. If ample cooling coils are placed in this water, and oil from the transformers is circulated through coils in this water, the cooling effect is better than if this water is passed through cooling coils in the transformers. Besides, the type of pipes through which the oil is circulated can be made and installed by any good pipe fitter and can be made as extensive as the operation may demand, whereas, in the case of the ordinary internal coils these coils are made by the manufacturers to suit the case and core of the transformer and are difficult to increase or modify.

In the case of oil circulation the pressure is applied to the oil and not to the water. This lessens the liability of water getting into the oil due to this cooling apparatus. We know that many cases of accident have been due to leaky coils in the case of water-cooled transformers.

Since external circulation permits larger cooling facilities of course oil circulation can be made to give much more reserve capacity where the same core and case are used. This is a very important matter in plants having a high peak load.

In warm, dry climates, such as the San Joaquin and Sacramento valleys of California during the dry season of mid-summer, it has been demonstrated that external circulation of oil cooled by water dripping over the cooling pipes in the open air has a very marked advantage over water circulation through internal cooling coils. We have no definite figures on hand showing these advantages, but a simple observation makes it evident that the advantage exists.

Wm. McClellan (by letter): In discussing this question it must be assumed that all mechanical features would be worked out so as to be thoroughly reliable. The expense of either system will vary according to the details and size of the installation, and in cases where there is a large number of transformers a considerable difference in the cost of the two systems might be found.

From his present point of view, the writer would be rather disinclined to favor the adoption of a forced-oil system. Such a system does certainly increase the risk of getting small amounts of moisture in the oil, and it is well known from recent experiments how much damage a very small amount of moisture can do in transformer oil.

In the forced-water type it is possible to keep all joints, except those which are brazed, entirely outside of the transformer case so that there is no risk from water except in case of a serious accident. The circulation of oil in the forced-water transformer is very uniform and takes place very quietly. The result is that moisture which accumulates gradually is very likely to be found at the bottom of the transformer and is undisturbed by the oil circulation; this would probably not accumulate to as great a degree in the forced-oil transformer.

One point in favor of the forced-oil transformer is the ease with which it permits of oil treatment. It looks very much as voltages increase as if we might come to the time when regular treatment of transformer oil would be imperative. In case of the forced-water transformer, this means removing it from the line, taking out the transformer oil, giving it some sort of a drying and purifying treatment, and then returning it to the transformer With the forced-oil circulation it would be entirely unnecessary to take the transformer off the bus bars since the oil could be treated at some point in the circulating system without affecting the operation of the station.

This will be all the more important should we ever arrive at the sub-station with all the transformers out of doors. As it is, with high tension transformers inside of buildings, there is some risk in removing oil from the transformers and allowing them to stand even for a few hours without oil if the cover must be taken off for any reason. It is very remarkable how quickly the insulation resistance of high-tension transformers will change gradually under these conditions.

A. L. Mudge (by letter): The extent to which forced-oil circulation for transformers comes into use will depend largely on the manufacturing companies. If they can quote materially lower prices per kilowatt, while making the same guarantees, it looks as if forced-oil circulation would almost entirely displace forced-water circulation for large installations. If there is little or no reduction in price, the water-circulation type has the advantage on account of greater simplicity of piping and connections, as no condensers, etc., will be needed. There will be less oil in the power house, and therefore, less fire-risk. In case of fire, if the oil has to be quickly drawn off from one transformer, it is necessary to open only one valve on a transformer using the water-circulation system, while in the oil-circulation system at least three valves have to be operated.

However, a material reduction in first cost in the case of large installations would probably offset the slightly greater complexity of the oil-circulation system. In most plants the oil reservoir could be located above the level of the transformers, thus doing away with one of the oil pumps.

Calvert Townley (by letter): To dissipate a given amount of heat requires a given quantity of water at a given temperature-difference from that of the part to be cooled. The nearer the point at which this water can be applied to the heated material the more efficient it will be as a cooling agent. Therefore, where water is expensive or limited in supply the method of cooling by circulating it in pipes within the transformer case uses the water in its most efficient manner and has a material advantage, However, where water is plentiful and inexpensive the method of forced oil circulation permits the use of larger quantities of water, producing a much greater cooling effect.

The first instance where oil was circulated for the purpose of cooling transformers, and with which I am personally familiar occurred in the Farmington River Power Company's station, near Hartford, Connecticut, in 1896. A number of step-up transformers of 150 to 200 kw. capacity each, self-cooling, were found to be heating abnormally. As a remedy the transformer cases were tapped and a 60-ft. pipe connected thereto, which pipe, wound in coil, was immersed in the tail race. A small circulating pump, belted from a convenient shaft, forced the oil through this pipe, and the result, at a negligible expense and no inconvenience, was an immediate reduction of temperature, so that the transformers worked well inside the normal margin of safety.

It will be noted that for water power installations the oil circulating plan becomes extremely simple and very inexpensive, as, where the tail race or other stream is available, no power-house floor space is needed for the cooling equipment.

There is a further advantage, that, whereas in transformers cooled by water forced through a pipe inside the transformer cases any leak in such pipe permits the escape of water into the transformer oil, thereby endangering the life of the transformer itself, with the forced circulation of oil such leak only lets oil escape into the surrounding water, and the transformer itself is in no danger of injury.

A paper presented at a Special Meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907.

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ENCLOSED STATION WIRING

BY F. O. BLACKWELL

In the design of a power station, the wiring is often given but scant consideration, and is fitted into such spaces as may be left over and not available for other purposes. In reality, a safe system of station wiring is as important as reliable machinery and should be given thorough consideration in making the plans of the building. Power houses have frequently been shut down by animals getting across the conductors and by

FIG. 1

materials accidentally coming in contact with them. Men working about a building may be killed or injured seriously by exposed electrical connections. Once started, it is impossible to say how much damage an arc will do with open wiring. In every case the service is likely to be interrupted.

Fig. 2.

In the power house of a few years ago, when the amount of power was relatively small, a short-circuit was not a serious matter; but to-day, with 50,000 or 100,000 h.p. concentrated in one plant, a much higher standard of station wiring is called for.

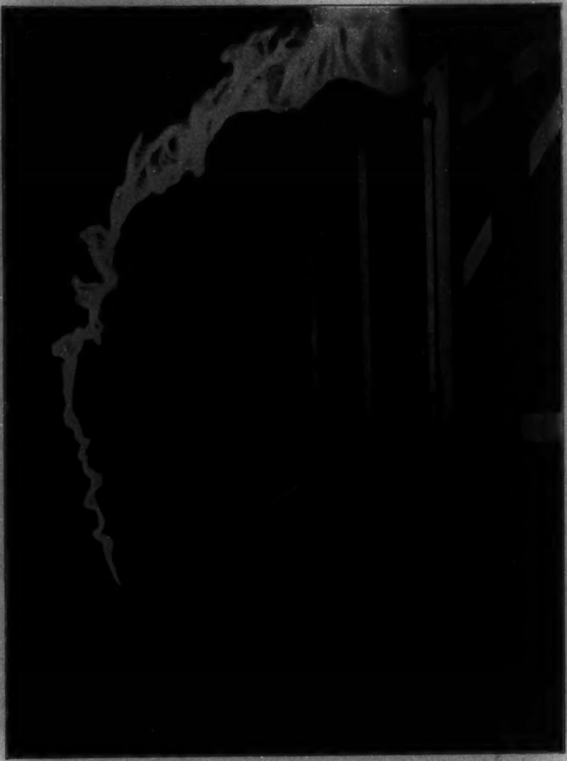

FIG. 3

With a large amount of power, the destructive ability of an arc is enormously increased, and the use of high potentials has made it possible for arcs, once started, to jump almost any distance if not confined.

The direct loss of income is large, but this is nothing to the indirect loss due to the depreciation in the selling value of the power output, caused by loss of public confidence in the reliability of the service.

The attached photographs will give some idea of high-potential arcs, although none of them has any great amount of power back of it, or is of as high potential as is now generally used.

Figs. 1 and 2 show arcs on a 40,000-volt 2,000-kw. system which, in a light breeze, jumped some 40 ft

Fig. 4

Fig. 3 illustrates a 30,000-volt air-switch opening with no load except the charging current of the line.

The metal vapor from an arc, even after the current has been interrupted, will often short-circuit conductors at a distance from the point where the arc started. Wires of high-potential circuits which are as far apart as it is possible to have them inside of a building, may be affected by arcs between low-potential conductors beneath them.

Lightning striking in the neighborhood of a transmission line has been known to cause a short-circuit after the discharge was over, due to the path of hot gas floating across the wires.

In order to prevent the occurrence of short-circuits, and to localize the damage should an arc start from any cause, the following elementary principles should be observed:

1. The system of connection should be as simple as will give the necessary control over the station.

FIG. 5

2. The conductors should follow the shortest and most direct line from generator to transmission line.

3. Each conductor should be surrounded and separated from every other by a continuous fire-proof barrier.

4. The circuits should be as far apart as possible.

Enclosed wiring has already become the accepted practice in important low-tension plants of from 2,000 to 15,000 volts, but is not used as generally for higher potential where the writer believes it is much more important.

Low-potential insulated cables, drawn through ducts or enclosed by split-tile or pipe coverings, are safe provided care is used to cover the cable joints at the manholes, as a cable-joint is a frequent source of trouble.

A single-cable tunnel, or duct system with common manholes through which all the cables in a plant run the length of a building is often employed, in which, if anything goes wrong with one cable, the entire power house is disabled. Accidents of this kind might be avoided by keeping the cables from each unit in a conduit at a distance from other circuits, and laying out the wiring so that each generator can be operated as if it were in a separate power station.

Where bare conductors are used on account of many connections, or where the potential is too high for insulated cables, the wires should be enclosed by substantial walls or barriers of brick, concrete, tile, or stone with only such openings as are necessary to get at insulators or connections. Covers should be provided for all openings.

A good example of enclosed wiring for 13,000 and 60,000 volts is shown in Figs. 4 and 5. These photographs are from the Toronto and Niagara Power Company's transformer house at Toronto.

DISCUSSION ON "ENCLOSED STATION WIRING," AT CHICAGO, ILL., MAY 24, 1907

C. W. Stone: I notice that Mr. Blackwell speaks of the connections being simple. I think this is a very serious matter and one that is not given the consideration it warrants. We try to make a system flexible by putting in all sorts of tie connections; then in order to save space and save cost we put in knife-switches. By putting in the knife-switches we court just what we are trying to avoid. The knife-switch may be opened by mistake. If it is opened under load by mistake there is a big arc, which may be whipped across and involve all the adjacent apparatus. Therefore, if possible, I think we should always try to keep each individual circuit entirely distinct, with no tie, and if ties are used we should use enclosed switches; that is, all switches in the form of knife-switches must be put in between barriers in order to confine the arc.

From Mr. Blackwell's paper it is quite evident the arc cannot be confined, if an arc at low voltage will jump forty feet. He also speaks of putting in barriers between the conductors. This is a very serious point with high-tension apparatus. If barriers are put between them, jumping distances are shortened and therefore the barriers must be put farther apart. This makes it almost prohibitive to install bus-bars in a bus-bar compartment, because the bus-bar compartment becomes as large as the station in order to allow safe jumping distances.

One other thing in connection with the keeping apart of the high-tension conductors, and that is the point where they are brought together in order to put in potential transformers. Potential transformers are connected across between phases, therefore resulting in a tie directly across between phases through a small device. This small device must be isolated and separated in such a way that if an arc forms or an arc jumps across the terminals it will not communicate between the phase wires. This means that each lead has to go through some brick barrier or soapstone barrier or through an insulator, which is bad at very high potentials. Then the current transformer is also used, a very serious thing with high potentials. It therefore would seem good practice to eliminate all secondary devices whatever from the high-potential side, installing all instruments on the low-potential side, running directly from the transformer, say, or the switch to the line, with nothing whatever connected to it.

L. C. Marburg: What Mr. Stone has said regarding simplicity of wiring connections cannot be endorsed too strongly. There is a tendency towards introducing flexibility to such an extent that the complications necessary to obtain it form a weaker point in the system than the original arrangement, the failure of which it is intended to take care of. In other words, while providing for an emergency occurring, say once in three years, we may be introducing the danger of a breakdown once a month.

With regard to enclosed wiring for 60,000 volts, Mr. Stone's remarks also appeal to me. Compartments for such high voltages become too large to be practicable, and it would seem that open work if properly designed, for example the type of installation adopted at the Ontario Power Company's plant at Niagara Falls, offers as much reliability as can be obtained. If wires are separated a sufficient distance so that an arc cannot hold, the installation is about as safe as it can be made. For voltages not higher than 30,000, bus-bar compartments and barriers between compartments and oil-switches have become the standard practice, at least as far as generating stations are concerned, but it would seem as if in many cases, wires were enclosed more than advisable. What is wanted are brick or concrete barriers between all bus-bars and between all switch connections, and as little brick or concrete work as possible should be introduced outside of this, so as to leave all wires and insulators visible and easily reached. For example, a bus-bar compartment may consist of one main vertical wall in the rear and a number of horizontal concrete slabs supported in front by means of small concrete columns. The bus-bars are placed in the horizontal compartments formed by these slabs, and switch connections are carried through the rear wall to switches located above or below these compartments, barriers being placed between the individual leads. This arrangement leaves all wires and insulators visible throughout, and seems superior to closed compartments and closed vertical risers between compartments and switches, as any leakage will be readily detected and as all insulators can easily be cleaned.

Instrument transformers on the high-tension side are of course undesirable, but, if the station contains a high-tension bus-bar with several independent outgoing lines needing protection, they cannot be done away with entirely.

P. M. Lincoln: Mr. Blackwell summarizes his paper thus:

1. "The system of connection should be as simple as will give the necessary control over the station". I think that all electrical engineers will agree with him there.

2. "The conductors should follow the shortest and most direct line from generator to transmission line". That, again, I think is a point where unanimous decision will be made.

Concerning the third, the vote will be by no means unanimous.

3. "Each conductor should be surrounded and separated from every other by a continuous fire-proof barrier".

I think the vote of the large majority would be "no" rather than "yes" to that, for the reason that the principal advantage of enclosing bus-bars, wires, etc., is to prevent a destructive arc from forming between those bus-bars, etc. Now the higher the voltage of a station, the less destructive become the arcs. With 2000 volts I presume there is about the maximum destruction that can possibly be got; at least I have had occasion to believe that from seeing what a 2000-volt arc will do with a very large amount of power behind it. I believe thoroughly, judging from my own experience, that 2000-volt bus-bars for any very large amount of power should be enclosed, by all means; but for the same amount of power at 60,000 volts or at 40,000 volts I do not believe the same thing holds. The destructiveness of an arc is in proportion to the volume of current and goes up with some power of that volume which I do not know—the square, at least, probably much higher—and, as I said before, the higher the voltage the less the amount of current available for producing destruction. That is one very good reason for omitting these fire-proof barriers at some point as the voltage of an installation goes up.

Another obvious and very good reason for omitting those barriers is the difficulty of obtaining insulation as the voltage goes up. Any material available for barriers must be considered as dead ground on these high voltages.

For these two reasons, therefore, I believe that there will be by no means unanimous assent to this statement in Mr. Blackwell's paper.

4. "The circuits should be as far apart as possible".

This will be assented to, I believe, by the majority of engineers. This statement is in contradiction to a certain extent to his third, because introducing fire-proof barriers practically means separating the wires double the distance that would be necessary without the use of fire-proof barriers. There is no fire-proof material that can be treated as an insulator at 60,000 volts and above; that is, no fire-proof material that is available for use as barriers that can be treated as an insulator at 60,000 volts and above.

E. N. Lake: I might give an example of how this problem was worked out in a small synchronous-converter sub-station designed for operation at a potential of 25,000 volts. I shall endeavor to show by a sketch the arrangement of the circuits and apparatus.

The transmission line wires were carried from the pole line to a cross-arm built into the parapet of the sub-station, thus making a design which was distinctly a part of the building structure. From this point the line wires went directly into the lightning-arrester tower. This tower was divided by a concrete floor into two stories, as shown. The back portion of the tower was further divided by vertical barriers running from the floor line of the lower story to the roof of the second story. These barriers were of brick four inches in thickness, built into both floors and the roof, thus giving the barriers a rigid lateral support. In the upper part of the structure the lightning-arresters were installed. Below the lightning-arresters the current transformers were located. Below the second floor the bus-bar chambers were located, which, instead of being arranged open on top were with closed top of concrete construction open below. In the lower story, or switch room were located the

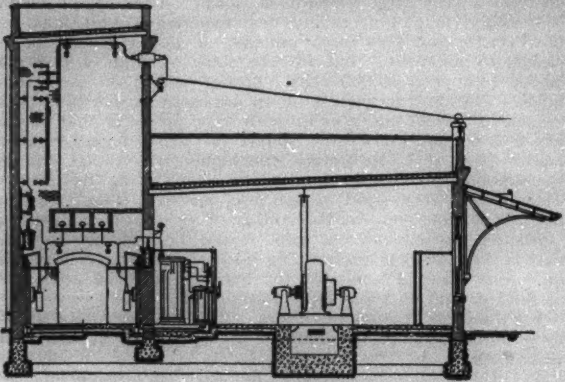

FIG. 1.

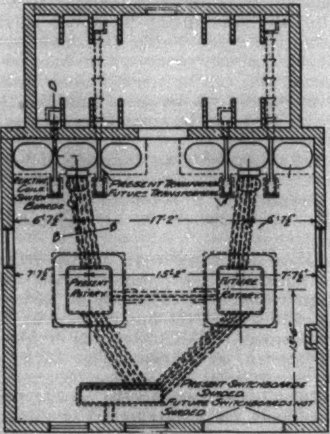
REACTIVE COILS SWITCH BOARDS
PRESENT TRANSFORMERS
FUTURE TRANSFORMERS
6'7½"
17'2"
6'7½"
B
B
7'7½"
15'2"
7'7½"
PRESENT ROTARY
FUTURE ROTARY
PRESENT SWITCHBOARDS SHADED
FUTURE SWITCHBOARDS NOT SHADED

FIG. 2.

oil-switches. The barriers which extended from floor to roof formed the barriers between the oil-switch compartments.

The transmission line was so situated that it was convenient to bring the wires in directly to a lightning arrester tower located at the back of the station. The switch on one side controlled an incoming or outgoing line and the switch on the opposite side operated as an individual rotary switch. At the division wall between the switch room and the rotary room there was an arched opening in the wall for the location of the potential transformers. This construction in general accomplished the end which Mr. Blackwell has brought out in his paper, viz.: that throughout the sub-station from the point where the high-tension wires enter the disconnecting-switches on the lightning-arresters to the point where they entered the top of the step-down transformers, every foot of that distance, the phase wires were separated by fire-proof barriers.

L. C. Marburg: When sub-stations are taken into consideration, the main arguments advanced in favor of enclosing leads in compartments do not hold. If twenty or thirty miles of transmission lines are introduced, the individual wires of which cannot be separated by barriers, there seems little use in separating these wires so carefully in a sub-station at the end of the line. If the building is fire-proof, a momentary arc that cannot hold cannot be considered very dangerous, particularly in view of the large resistance introduced by the transmission line between the generating station and the short-circuit. Compartment work in every 200- or 300-kw. synchronous converter station would involve considerable expense.

J. D. Jamieson: It has been my fortune to see some of the extremes in high-tension work, represented in one case of barriers carried to an excessive degree of refinement, and in another case, where the potential was within 10,000 volts of the first, with no attempt to provide barriers between the conductors. The second case I cite bears out the remarks just made about the inadvisability of providing barriers for extremely high potential. This course might be advisable from the standpoint of normal operation, or might take care of any possible rises in potential which might be occasioned, but there is another phase of the matter with which a large central station has to deal; that is, accidental contact. With a 60,000- or 50,000-volt system of a capacity of perhaps 60,000 kw. and a reasonable number of distributing circuits, every precaution has to be taken against accidental contact, and I think if a large station were put up in the fashion mentioned, without barriers, that we would find with a working construction force of 50 to 100 men there would be quite a lot of trouble due to the absence of barriers.

With regard to the addition of knife-switches to the system, it has always been the endeavor of the company with which I am connected to do away with the knife-switches to the extent of putting disconnecting points in a circuit in enclosed partitions; that is, disconnecting-switches, which are necessary in series with oil-switches, are put in the same compartment

On the higher potentials it is not possible to get oil-switches which are equipped with disconnecting appliances. Therefore we are forced to install knife-switches outside the oil-switch, which call for additional barriers. In some cases we go further than to provide barriers, we provide the barriers and then insulate the conductors inside the barriers. This practice has been pronounced superfluous by some, but we have had instances of the worth of such construction. There have been cases where an enormous flow of current, due to the accidental interruption of the circuit, had caused the conductors inside the barriers to be dislodged, and to rest upon the concrete shelves. In that case we found that the addition of insulation to the conductors prevented a very serious disaster. I think that barriers should be used in all cases, and further, that although there is no fire-proof material that is an absolute insulator, the effect of the short-circuit is greatly decreased even though the arc holds between the conductor and the barrier.

Fay Woodmansee: We all agree, I think, that the station wiring must be as simple as possible, and then after that the question of separating depends entirely, I believe, upon the voltage, the capacity, and also as to whether the station is a generating station or whether it is a sub-station located at the end of a line. In a sub-station located at the end of a line, I think the same as Mr. Marburg does; after a number of miles of line that has been unprotected, why in the station separate the wires from each other by barriers? In the station there is less liability for anything to get across the wires, because the wires are placed close to the ceiling. There it is almost possible for any material to get over them to cause a short-circuit and shutdown. Consequently the additional expense is not warranted, I believe, in barriers between poles of lightning-arresters, or anything which may cause an arc in its operation. But in the power house proper, where the question of keeping the potential on the bus-bars is very important and there are a number of men working in the station, I believe that the bus-bars should be separated from each other by some fire-proof barrier, as much to protect the life of the people who may be working in the building as to make the service safe. I think in a good many cases our stations are made much more complicated than they should be.

The question of running leads from bus-bars I think is a very important point to consider. It is oftentimes easier to insulate the bus-bars and run them lengthwise of the station and thus cut down to a minimum the number of feet of cable required. These cables can be run and protected in such a way that it is practically impossible to cause trouble.

P. M. Lincoln: I am thoroughly in accord with what Mr. Woodmansee has said with regard to the protection of life in the station. I think that is absolutely the first requisite that should be taken into consideration in making a switching layout. However, I do not believe that that element compels us to enclose each bus-bar or each wire in a fire-proof barrier. In fact, my own opinion is that the modern tendency is rather toward doing away with all buildings than putting buildings around every individual wire and piece of apparatus in a station. I think the time is coming when the bus-bars, transformers, switches, and practically everything else of that kind will be put out in the weather, and a building put around only the apparatus that it is absolutely necessary to cover, such as instruments and things of that character.

E. N. Lake: I cannot quite bring myself to agree with Mr. Woodmansee or with Mr. Lincoln in regard to justifying the additional expense of barriers. In a given case, where barriers were used in a fire-proof sub-station constructed of brick, concrete, and steel, the additional cost for the introduction of the barriers was probably twenty-five or may be fifty cents per kilowatt. It seems to me that such additional expense is fully justified in the matter of safeguarding life. I think that the protection of life is one of the most important things that we have to consider, it is in fact *the* most important thing to consider in designing stations for higher potentials.

P. B. Woodworth: Will Mr. Lincoln please explain how he is going to safeguard life when he has his wires out in the open with no house around them at all?

P. M. Lincoln: The space up in the air is very easy to obtain. All there is to be done is to put the station out of reach. An ordinary transmission line is not considered dangerous; it is out of reach. Exactly the same thing can be done with a sub-station. It seems to me that, if it is logical to put fire-proof barriers around the individual wires in a sub-station, it is just as logical to run those fire-proof barriers clear back to the generating station. That reduces the fire-proof barrier proposition to an absurdity.

E. N. Lake: If I were going to carry the transmission line wires from the sub-station back to the generating station in such a location that it was possible for the men in their daily work to come in contact with them, I would most certainly put the barriers all the way from the sub-station to the power house.

W. B. Jackson: Doesn't that reach the actual kernel of the matter? Namely, where it is possible for the wires to be touched by the employees in the regular performance of their duties, the wires must be protected by the fire-proof compartments or by separating walls of some kind, but as soon as the wires are carried out of that zone then let them be free. That is getting to be common practice, especially so in plants on the Pacific coast, and it seems to be the logical way to arrange high-tension wiring.

P. M. Lincoln: I think there is no disagreement on that point, that the most essential thing in putting in a sub-station must be to protect life, but I do not agree that putting fire-proof barriers around the wires is the only way to do that. Keep them up out of the way, where they can not be touched by the man in the regular discharge of his duties. That is one way. There are other ways, such as putting ground wires under them or around them, as Mr. Stone has suggested. I think, however, on the essentials there has been no disagreement, no very material difference of opinion among us.

Dugald C. Jackson: Your suggestion that the future substation will be out in the air reminds me of the stations of certain of the Western plants. They have step-down sub-stations, not converter sub-stations which require attendance, but step-down sub-stations, where the building consists practically of a light wooden framework with corrugated iron over it, and the line that passes over it drops down through the roof through suitable terminals, and the wiring is run to the transformers through ordinary fibre conduit, using the usual linen covered wire. That makes a sub-station that approaches the limit of simplicity. It is almost the equivalent of having the whole thing out of doors as perhaps it is even cheaper than to erect the structure on an elevated platform, and it also does this, which I think perhaps is likely to militate against Mr. Lincoln's proposal to put everything outdoors; it protects the transformer terminals and such switching terminals as are needed from the beating of the weather,—the sleet and rain and that kind of thing that one is bound to meet and which these terminals practically need to be protected from.

Edwin W. Olds: When you call upon me to speak upon the subjects that have been so interesting to-day, you are calling upon one who, while old in years, and in name, is very young in that part of the business. We are just putting in our first single-phase alternating-current direct-current car equipments. Electrical engineering is somewhat out of my line, but is very interesting, and some of the points that have come up have appealed to me in a practical way. I am not a technical man in any sense of the word. What little knowledge I have has been pounded into me in the good old way.

I have noticed in our direct-current operation in Milwaukee that in certain sections of the city where there are a great many telephone and other wires it is very seldom that any of our cars are struck by lightning; but in other sections where the telephone and electric light wires are not so plentiful, there is trouble with our cars. From my standpoint, this is quite conclusive evidence that a grounded conductor is of a great deal of importance, for, if it will protect our direct-current feeders and trolley lines, why should it not protect the higher potential wires that are so much more apt to be disturbed by the lightning.

Bertrand P. Rowe (by letter): In following the development of systems of station wiring in connection with switchboard installations, we begin with the single generator and the primitive system of open wiring carried on porcelain knobs, which was undoubtedly borrowed from the earlier experience of the telegraph companies, As the fire hazard from poor electrical wiring became more universally recognized, insurance companies from time to time insisted on better spacings, better insulation, and absence of combustible material. The sizes of generating plants have increased, and the amounts of power that have been concentrated on single sets of conductors or bus-bars have reached such proportions that the old-time methods would not suffice for their installation. With this new set of conditions, the underwriters have not meddled. They have found that the owners of generating stations are building fire-proof plants with concrete floors, and structural iron and masonry walls, and they have no regulations to offer regarding the installation of these heavy capacities beyond what are already in vogue for those of lighter capacity. Their fire-risks in such plants are small, and they are interested more in applying their rules to the wiring of factories and dwellings where there is a fire-risk.

The designers of electrical power stations, however, have found that with increased capacities at higher voltages there exists the danger of serious damages and shutdowns, due to arcs starting between conductors, being fed from conducting gases from vaporized copper with the power of large generating units concentrated behind them.

With low-tension systems, from 125 to 250 volts, this danger did not exist, even with thousands of amperes in bus-bar capacity, fed from storage-batteries, because the voltage was too low to maintain anything but a short arc. Difficulties of this sort have been noticeable in plants of from 2000 volts and upwards, principally because 2200 volts is the lowest high-tension voltage at which large amounts of power are concentrated.

In order to prevent arcs between conductors in smaller installations, the conductors were insulated. The practice in these larger installations is to use bare copper bus-bars, and insulate them by air-spaces, inclosed in fire-proof cells. All cable connections are likewise carried in cells, as well as all apparatus liable to cause an arc.

The practice of isolating the conductors has been followed in all modern heavy capacity plants up to and including 15,000 volts. The reason for the practice will be well exemplified if one starts out to design open-link fuse-blocks. It will be seen that a fuse for 250-volt service may be constructed very easily which will carry normally 2000 or 3000 amperes, and rupture the circuit on an overload of 25% without difficulty.

Now if one starts to design 500-volt fuses, he will find that a fuse to blow at 1200 amperes is a pretty difficult problem, and with plenty of power behind it, the fuse-block will be hard to construct which will not be destroyed by the arc. The rupturing of the established arc will be quite a difficult thing without careful study and design.

Now if one goes a step further and tries to design a 2200-volt fuse-block one will get into difficulty when the capacity gets above 300 or 400 amperes. And likewise one will find it difficult to design a successful 3300-volt fuse-block for a larger circuit than 200 amperes.

It follows, then, very readily that, as the voltage rises, heavy capacity currents become more difficult to break; they maintain themselves vigorously, destroying all material which may intervene. The tendency, therefore, in all modern installations, is to suppress all high-voltage arcs by eliminating as much as possible the air-break switching devices, and by using oil-switches, and placing barriers between conductors.

What the station engineer is doing for his own protection, is heartily seconded by the Board of Fire Underwriters, who are leaving the problem alone because not so vitally interested. And the problem is undoubtedly being handled generally in a much more satisfactory way than they themselves would feel free to demand.

Some time ago the underwriters inspected the plant of the Ontario Power Company at Niagara Falls, which has all of the low-tension conductors and switching devices in fireproof cells. The writer was much impressed by being told by these inspectors that they had only one recommendation to make regarding that entire installation, which was that a fire hydrant be placed at each corner of the building. They stated that the modern construction was ahead of anything they had seen at that time in the way of fire-proofing.

In the selection of barriers, the engineer is limited at present because the ideal commercial barrier does not exist. The common practice is to separate all conductors from each other and from grounds, using such distances that concrete or brick barriers may be used with safety. At high voltages, these substances must be considered as grounds, since they absorb moisture, and this makes necessary much wider spacings than if the barriers were of insulating material. Soapstone, while a little better than these, is still an absorbent material, unless impregnated. Porcelain is too dear, and glass will not stand an arc. Asbestos lumber and transite make admirable fire-proof barriers but are poor insulators.

Probably the nearest perfect barrier would be an impregnated material like soapstone, and this is of course expensive. No cheap insulating barrier being known, the common practice is to support all conductors on suitable insulators and rely on the grounded barriers for fire-proofing. The best practice assumes that all insulated cables are subject to deterioration, and unless they are protected by lead coverings with suitable end-bells, they are invariably as well supported on insulators as a bare cable should be. This insures permanency.

For installations of voltages above 15,000, the cellular construction is not so prevalent. But the subject for high-tension wiring for these voltages deserves great attention, because, as stated by Mr. Blackwell, this part of the installation usually gets scant attention when the building is designed. The very best modern practice is to lay out this system of wiring in advance and design the building to suit.

The writer does not agree with Mr. Blackwell that the use of barriers and fire-proofing for very high tension wiring is at present more important than for wiring whose potential is from 2000 to 15,000 volts, for the reason that at the very high voltages now employed the sizes of conductors are very small. They will usually burn away instead of maintaining a fierce arc, such as might be expected if heavy masses of copper are short-circuited. The practice of most station designers seems to sustain this view of the case.

One of the reasons why the use of barriers and cells for conductors has not been more extensively carried to higher voltages is because the generating voltages now deemed practical are all below 16,000 volts. Whenever the manufacturers are ready to put commercial generators on the market to generate current at 20,000 volts, this construction will be seen adopted universally for that voltage where heavy capacities are used. There are even now some cases where large quantities of power are to be distributed at 33,000 and 45,000 volts, and the cellular construction is advisable because of the heavy capacities that are carried on the bus-bars.

In the writer's opinion the use of the barriers and cells, such as are common with the lower voltages, are an unnecessary refinement in a majority of cases. In almost every plant operating at pressures of 45,000 volts and upward, the potential of the transmission system is raised to such a value that, with a given line-loss, the size of conductor can be made as small as mechanical considerations will warrant, to save expense in the transmission line. So long as this practice obtains, and unless large amounts of power are concentrated on high-tension bus-bars by banking the step-up transformers, there will seldom be large masses of copper in the high-tension system to maintain an arc. In fact the condition where heavy conductors may be required on the high-tension system of 45,000 volts or more, can be, and usually is avoided, by feeding separate banks of transformers into their own transmission lines, with a relay bus-bar of small capacity to enable circuits to be transferred from one bank of transformers to another in case of trouble.

In a modern power station, using oil circuit-breakers, if the idea of barriers between all high-tension conductors, irrespective of capacity, were logically carried out, it would be more necessary to require these barriers between the wires on the transmission line where the conditions of atmosphere and moisture are more conductive to short-circuits, than to require them in a properly wired power station where they are enclosed and dry and as well separated as they are on the poles. Where air-break switching devices are used, however, fire-proof barriers are certainly necessary if there are conductors near enough to the arc to cause any apprehension.

Another argument against the use of barriers between very high-tension conductors in power stations is the increased size of station often required if the idea is carried out properly, owing to our inability to obtain a satisfactory insulating barrier. As stated previously, all known barriers, except those of glass or porcelain, must be considered as grounds for high-voltage circuits, and glass and porcelain barriers are not practicable because of brittleness and expense. Therefore, we are forced to use grounded barriers, and the introduction of these barriers between the high-tension conductors in a station compels us to space our conductors much farther apart than they are for the transmission line, to provide sufficient insulation distance. It will be found that to install these barriers properly, a larger amount of room and expensive construction will be required than is usually warranted.

The most practical way to handle the problem is to confine all apparatus which is liable to arc, and separate the conductors by suitable air-spaces, using insulated conductors for the sake of safety. A time may come when reliable insulating material may be obtained in the form of fire-proof tubes through which these conductors may be carried, and which will be sufficient insulation to allow closer spacing of conductors. In such a case the saving in space in a power station will be justification for using them.

The writer believes thoroughly in providing an insulating covering for all high-tension conductors carried in air in the interior of a power station as a safeguard against accidents due to accidental contacts. While it is preposterous to think that cables carrying 60,000 to 88,000 volts can be insulated for safe handling, yet the writer believes that they should be as well insulated as possible to prevent workmen from being killed by contact with poles or other implements.

In addition to this the wires should be marked with danger signals and warnings to remind the unwary. These precautions may save loss of life and bills of damages which are usually awarded against power companies who are found guilty of carrying their deadly current on bare conductors where workmen may be near enough to be shocked.

It may be possible to insulate the conductors with some of the special tubing now on the market, with some form of impregnated oiled muslin next to the cable so that there is scarcely any danger to the cables, by preventing possible arcs. The writer believes that the best and most conservative practice in most cases will be to try to provide such arc insulation as this, and then support the entire insulated cable on insulators with good free air spacings between all adjacent conductors and to ground.

Stephen Q. Hayes (by letter): The writer agrees with three of the principles enumerated, but does not believe that in stations where voltages of 33,000 and upward are obtained by means of step-up transformers "each conductor should be surrounded and separated from every other by a continuous fireproof barrier", and for the following reasons:

First, the violence of an arc and the destructive effect of a short circuit seem to depend more on the amount of current than power available, or for the same amount of power would diminish with increase in voltage.

Secondly, the short-circuit current available on the secondary side of a transformer is less than that which would be supplied by a generator wound for the same voltage and connected directly to the bus-bars. The use of the transformers introduces a cushioning effect.

Thirdly, as the fire-proof barriers offer a more or less perfect ground for high-voltage circuits, the striking distance from wire to ground has to be greatly reduced over what could be obtained with open wiring in the same space.

Fourthly, the use of enclosed bus-bars and wiring ordinarily necessitates several floors or galleries and a more expensive building and more costly structures than the open wiring.

Fifthly, it is more difficult to inspect and repair bus-bars, wiring, disconnecting-switches, lightning-arresters, etc., that are boxed in masonry compartments and only visible and accessible by the removal of doors than if everything is in plain sight. Incipient trouble will be noticed far sooner with open wiring than with enclosed and inspection will be more frequent and thorough if the station attendant in a few minutes' walk can see everything, than if he had to remove several hundred doors and visit two or three floors to examine the condition of the apparatus.

As Mr. Blackwell refers particularly to the Toronto & Niagara Power Company's transformer house at Toronto as a typical example of the enclosed wiring and bus-bars, it might be stated that at the time of a recent visit to that station in February, the static discharge apparently from the 60,000-volt wiring and bus-bars could be heard all over the building. This trouble may have been remedied since that time, but is one far more likely to be met with in a system of enclosed wiring than in a system of open wiring such as that of the Ontario Power Company's Plant at Niagara Falls.

C. W. Hutton (by letter): The enclosed station for the higher potentials has not, as stated by the author, been given the attention which it appears its importance demands. Cable insulation for potentials of 50,000 volts and upwards seems out of the question and the only alternative seems to be the use of long bus-bar ducts with the conductors mounted on suitable insulating supports, (the ordinary line insulator being the most common practice). The arrangement of the apparatus which would seem most simple and satisfactory would be to set the transformers in a straight line and in groups. A moderately heavy brick wall should be built immediately back of the transformers with openings suitably arranged for the passage of the high-potential wires from the transformers, which should be set with their high-potential sides next to the wall. Suitable open-air disconnecting switches should be interposed between the transformers and the openings in the wall and be mounted upon the brick wall immediately above the transformers. Three bus-bar ducts (considering that three phase working is to be used), preferably of tiling on account of its many desirable features, each having a section of approximately 2 ft. 4 in. by 2 ft. 6 in. high should be arranged one above the other immediately back of the brick wall, the bottom of the lower duct being approximately level with the tops of the transformers.

Sectional bus-bars and line oil-switches should be arranged in tile compartments immediately back of the bus-bar ducts, the bottom of the compartments being on a level with the bottom of the lower bus-bar duct. Suitable hand-operated oil-switches for plants of from 10,000 to 15,000 kilowatts can now be made up in three-pole units at a cost of about $175.00, including the remote-control apparatus, so that the liberal use of oil-switches is not prohibitive on account of expense.

One of these three-pole units can be very conveniently installed in a space of 5 by 5 by 10 ft. long. From the oil-switches used for the individual line circuits, the lines pass through suitable wall openings to the outdoor disconnecting switches mounted on poles immediately adjoining the building, thence to the transmission lines. Remembering that all oil-switches have open-air disconnecting switches on both sides, it will be seen that it is never necessary to open the air-switches under load. Practice has shown the above arrangement to work out very simply in construction and highly effective in operation.

The low-potential station wiring at any voltage from 15,000 down has been so well standardized that time will not be taken to discuss it.

Wm. McClellan (by letter): There is little doubt that the enclosed wiring is much more desirable in power stations and sub-stations when the voltage is less than say 20,000. Above this voltage, engineers would do well to favor conditions which will permit of open wiring as much as possible. It is a note-worthy fact that, for the same power, as the voltage increases, the arc, although capable of jumping over longer distances, becomes in itself less destructive. It may also be noted that about the only time an arc can start in a properly designed installation is where open switching is done. So far as bus-bars, tap connections, and apparatus terminals are concerned, there is no danger whatever in open wiring. The remedy then is to make use of oil switches. It is usually found that for very high voltages the amount of space required and the cost of complete installation would be far greater for the enclosed wiring than for the ordinary open type. It is quite apparent that the trend of design for very high voltage sub-stations is towards an inclosure as small as possible. The writer's conception of the future very high voltage sub-station, or step-up portion of a power house installation, is a small switching compartment enclosing the control switches and meters, with transformers and remote controlled oil-switch all out of doors. Under these circumstances the lightning arrester is about the only place at which it would be possible for an arc to start. As this will probably be out of doors anyway, it does not affect the general question. Should we be so fortunate as to get all that the electrolytic arrester seems to promise, we should have no trouble here.

L. A. Herdt (by letter): Large hydroelectric plants of recent design, operating under high voltages and developing large amounts of power, show so much variety in the arrangement of the electrical apparatus as to suggest wide differences of opinion among the designing engineers as to what is considered necessary and advisable to guard against the spread of arcs and to protect the apparatus from trouble if it exists in one part of the plant.

In some cases the isolation of the high-tension apparatus and conductors is carried out in such a way that each conductor is surrounded and separated from every other by incombustible walls and barriers. Transformers are placed in pits and isolated from one another by heavy masonry fire walls. On the other hand, in one of the largest hydroelectric plants of this country, the high-tension bus-bars and disconnecting-switches are placed in an open room without any intervening sections or barriers; the transformers are walled in, but in groups of three.

In another installation of considerable size the transformers will be found all placed together in one room, the high-tension wiring is open without barriers of any kind; considerable distance is allowed between the conductors and this has, so far, afforded sufficient protection.

The writer, however, agrees with Mr. Blackwell that high-tension apparatus and conductors require to be guarded against the spread of arcs, and should be protected from fire spreading from adjoining apparatus or from external sources. This protection is best secured by fire-proof barriers, but the extent of this protection and the expenditure thus incurred should bear some relation to the amount of power generated and the revenue to be derived from the sale of the power. The writer is of the opinion that when there exists a number of high-tension transmission lines carrying large amounts of power, each transmission line, with its high-tension switches, bus-bars, lightning-arresters, and transformers forming one unit, should be separated altogether by fire walls and the like from the apparatus belonging to another similar set. The high-tension bus-bars common to all the different units should be constructed with great care, and whether placed in continuous fire-proof barriers or not they should be provided with disconnecting- and tie-switches, so that each unit could be operated as a separate plant or could be coupled with the others when found advisable.

A paper presented at a special meeting of the American Institute of Electrical Engineers, Chicago, Ill., May 24, 1907

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POTENTIAL STRESSES AS AFFECTED BY OVERHEAD GROUNDED CONDUCTORS.

BY R. P. JACKSON.

This paper is a theoretical investigation of the potential gradients and the equipotential surfaces about grounded conductors suspended in the air, and also about metallic towers for supporting transmission lines. It is obvious that equipotential surfaces surround all conducting material subject to static strain, but the position of these surfaces and the gradient of change at different points are usually difficult to determine.

An example is furnished in the overhead grounded wire sometimes used as a protection for a transmission line against lightning. Such a wire placed above a transmission line serves two purposes: first, it interposes a grounded conductor between the sky and the transmission line, and tends to relieve the line from direct strokes (the effectiveness of the grounded wire for this purpose will probably depend largely on its size and the frequency with which it is grounded); secondly, a much more frequent condition, however, is the stress due to induced potential between the transmission wire and ground. If we make an assumption which seems reasonable that there is a potential stress between a cloud and the ground, and that the distribution of this stress is nearly uniform, at least in the vicinity of the earth's surface; that is, that the potential due to the cloud is proportional to the height above the ground, and the potential gradient is, therefore, approximately a straight line near the ground, it is possible to determine in what way this gradient will be altered by the presence of a grounded conductor some distance above the earth.

The potential at a point near an indefinitely long cylinder remote from other conductors is proportional to the logarithm of its distance from the centre of the cylinder. If the potential at the point also tends to be proportional to its distance above the ground, its resultant potential will be the algebraic sum of the two. Obviously, the surface of the ground is itself an equipotential surface; for if it were not, current would flow from the points of high to those of low potential, and it would immediately become an equipotential surface. This fact, that the earth is conducting, cannot be represented mathematically, so it is necessary to assume an image of a charged object the same distance below the earth's surface as the real object is above. and that its charge is always of opposite sign. The surface of the earth then becomes of uniform potential without assuming that it is conducting. The equation for potential of a point near a grounded wire then becomes

$$C\,H - K \log \frac{R}{r} = P \qquad (1)$$

where H is the distance of the point above the ground, C and K are constants, and R and r are distances of the point from the image and the wire respectively. P is then the potential of the point taken. By taking the point on the surface of the grounded conductor, H, R, r, and P become known. The constant, C, is determined by the assumed gradient, so the constant K may then be determined, and if logarithms to the base 10 are used, will include the proper modulus.

In Fig. 1 a 0.5-in. wire 50 ft. above the ground has been assumed. The gradient is taken at two per foot, so that if the wire were not there the potential at the point where it has been assumed would be 100. This is convenient so that values deduced may also be used as per cent. ratios. The equation becomes approximately

$$2\,H - 30 \log \frac{R}{r} = P \ (2).$$

All the curves of Fig. 1 are calculated from this equation.

It may be seen that at no point directly beneath the grounded conductor is the potential greater than 52. Curve G becomes the gradient instead of N. The meaning of this is that a transmission wire placed, say 5 ft. below the grounded wire, would, when there was a charged cloud overhead, have a potential of about 55% of that which would exist if there were no grounded wire tending to cause a charge to leak from ground to the transmission line. Again, after the cloud has discharged, there would be only 55% as great a potential on the wire, and consequently only 55% as great a charge to escape suddenly to ground. In other words, the curves do not indicate that complete protection is obtainable from a single wire, but that under certain conditions a material reduction of static stress will occur. The amount of this reduction is dependent on the relative positions of the transmission line and the grounded conductor.

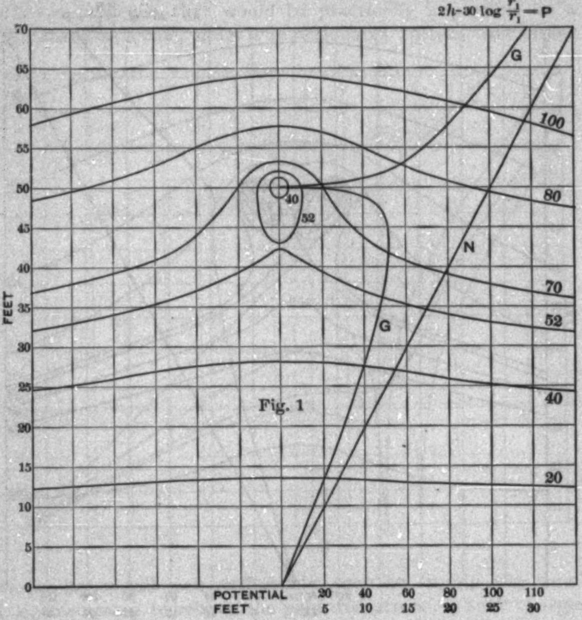

Fig. 1

The equation given for a single conductor may easily be elaborated to cover any number of conductors of various sizes, distances apart, and height above ground. By taking the point for which the potential is determined by equation (2) on the different wires in succession, as many equations will be obtained as there are constants, so all may be determined.

The equation for two wires, 10 ft. apart, 50 ft. high, and 0.5 in. in diameter, becomes

$$2\,H - 23\,\log \frac{RR}{rr} = P.$$

Fig. 2 shows the corresponding curves. It will, of course, be true that the protected area is considerably larger. Fig. 3 shows the assumed gradient, a straight line reaching a value of 100 at a height of 50 ft., and also shows the gradients on a medial plane for one 0.5-in. wire, 50 ft. high, two 0.5-in. wires, 10 ft. apart, and 50 ft. high, and the same plus another wire between them and 5 ft. higher. Curve 1 being for one wire, Curve 2 for two wires, and Curve 3 for the three wires, respectively. If a number of wires were arranged either in a horizontal plane or cylindrically with the concave side towards the earth, there would be a large

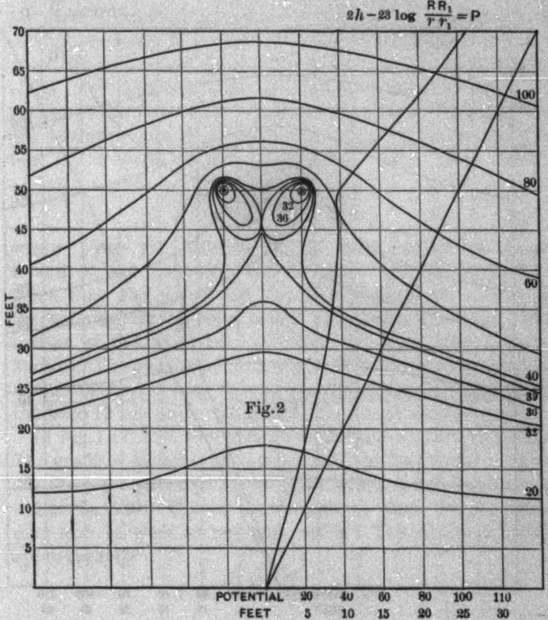

Fig. 2

area of low potential covered, which would probably be a comparatively safe location for a transmission line.

The above deductions are based on the assumption that the transmission wires are completely insulated, both from the ground and from the other parts of the circuit not affected by the cloud potential. Insulated uncharged conductors of small dimensions in the direction of the static stress have no appreciable effect on the static field about them. The above is a condition, however, that would be practically impossible on a real transmission line, since it is reasonably certain that either the insulators will leak sufficiently soon to supply the small charge necessary to relieve the potential stress, or such charges will be supplied through a grounded neutral, if there be one, or by the capacity of the remainder of the circuit not affected by the cloud potential. In any case the gradually developed stress due to the cloud will be relieved by charges appearing on the transmission wires, but when the cloud suddenly discharges by a lightning flash, the charges on the line wires escape suddenly either lengthwise on the wires and into power stations, or over insulators at the points where the stress is greatest.

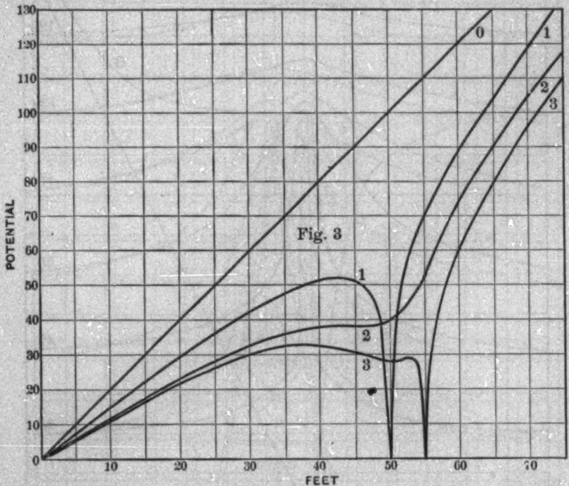

Fig. 3

By the fundamental principle of the conservation of energy, the potential stress which will cause a charge to appear on a wire will be reproduced in the opposite direction by that charge, if the original stress be removed. This also holds good when a grounded wire is placed above a transmission line, so although curves of Figs. 1, 2, and 3 are calculated on the basis of perfectly insulated line wires, they hold equally good for an actual transmission line where charges could readily find their way to the parts of the line under stress by the paths previously mentioned. This can be proved mathematically, independently of the principle of conservation of energy referred to above.

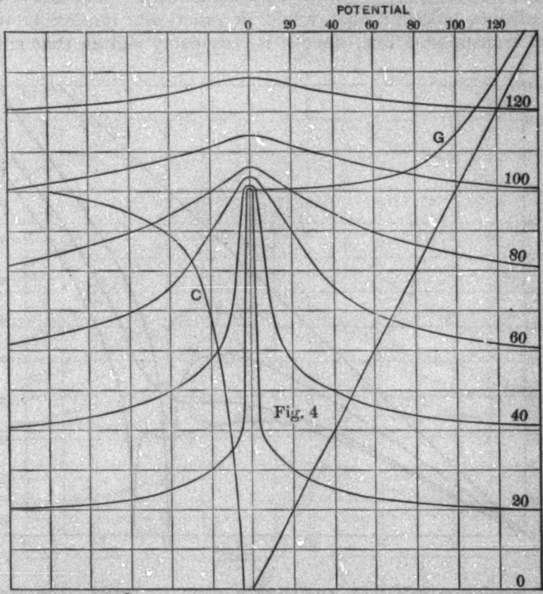

Fig. 4

POTENTIAL GRADIENT-G,
COMPARATIVE CHARGE-C

EQUIPOTENTIAL SURFACES. ONE-INCH CYLINDER 50 FEET HIGH

If the line were so insulated that only a partial charge could leak to the transmission wires, the primary stresses would be reduced somewhat, but the grounded wire would still have the same beneficial effect.

It is obvious that to get the full benefit of the grounded conductors, they should be thoroughly and frequently connected to the ground, as their effectiveness consists in releasing their own charge at the moment of a lightning flash, and immediately receiving another of opposite sign from the ground. This latter charge is then of opposite sign to that which still remains on the transmission wires, and serves to reduce the potential of these wires.

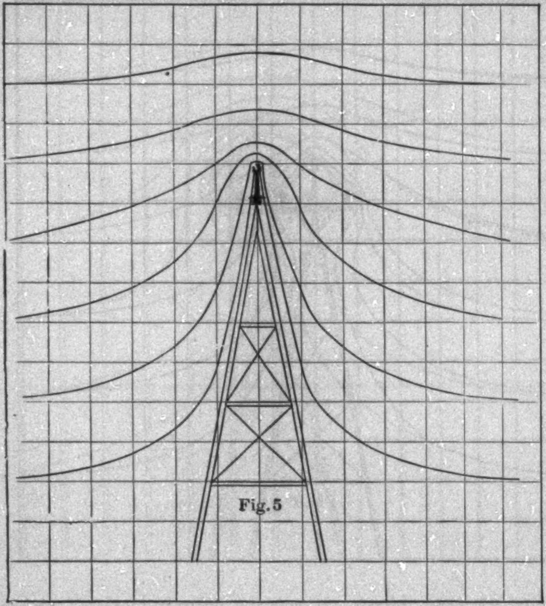

Fig. 5

It will be noted in Figs. 1 and 2, that the lines representing the equipotential surfaces are closely crowded together on the upper side of the grounded wire. This characteristic is much more marked in the case of a tower or spire projecting toward the sky. The potential of a point near such an object is much more difficult to calculate, so in Fig. 4, a 1-in. conducting vertical cylinder 50 ft. high was assumed, and the equipotential surfaces calculated. Curve *C* shows approximately the proportional charge at different points along the cylinder. Curve *G* shows the potential gradient from the top of the cylinder. It is seen that the charge density becomes relatively very great at the top of the pole or cylinder, and that the change of potential is very rapid for the first two or three feet above the top of the cylinder. This is a condition tending to produce leakage into the atmosphere, or corona effect, such as the St. Elmo's light seen at times on mastheads of vessels.

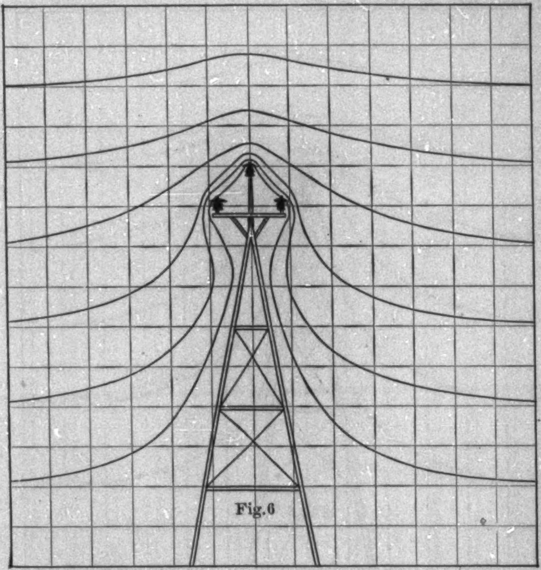

Fig.6

Apparently, if an insulator were placed on the top of this cylinder, and a high-potential conductor were carried by this insulator, there might develop a conducting state in the atmosphere about this insulator that would cause it to flash over, especially if there were any sudden rise of potential on the conductor carried by the insulator. Fig. 5 shows one view of a metal tower under this condition, and Fig. 6 another view.

Fig. 7 shows the natural suggestion for relief. If the tower structure were carried higher, and the insulators and transmission wires suspended downwards, the desired result would be obtained without the additional shielding device shown in Fig. 7.

All the discussion given in this paper is, of course, pure theory, and if there were never any insulators broken, or other trouble from lightning strains, it would have no practical value. Insulators are broken, however, especially those carried on metallic towers. So, while the information given in the curves does not indicate to any degree how much trouble can be eliminated by the devices discussed, there seem to be suggestions as to the most effective arrangement of such devices. If line insulators are subjected to frequent stresses of a value five times that which they will stand, a reduction of 50% would

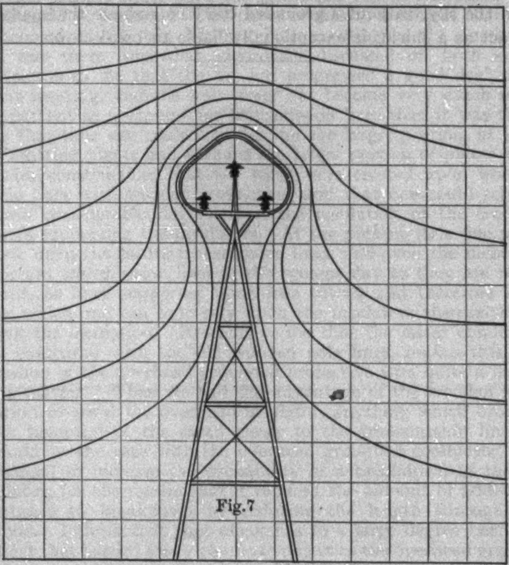

Fig. 7

not avail much. If, however, the average of normal stresses to which they are subject are only 150% of the break-down value, a reduction of one-half in these stresses may eliminate a very large amount of trouble.

The general conclusions are as follows:

1. Properly placed and grounded conductors above a transmission line ought materially to reduce the electrostatic stresses to which the insulators will be subjected.

2. An insulator interposed between a high metallic structure and the sky, without a grounded conductor above the insulator to act as a shield, is exceptionally liable to break down.

DISCUSSION ON "POTENTIAL STRESSES AS AFFECTED BY OVERHEAD GROUNDED CONDUCTORS," AT CHICAGO, MAY 24, 1907

P. M. Lincoln: I consider Mr. Jackson's paper an interesting discussion of a very important topic. It is, as Mr. Jackson admits, purely a theoretical discussion of the amount of protection which may be expected from an overhead grounded wire. Many transmission line operators believe that this overhead grounded wire has no virtue; others believe that it has a great deal of virtue. I expect that there are representatives of both camps present and I hope the discussion will be complete.

Dugald C. Jackson: This paper relates to a subject that was discussed at the last Niagara Falls meeting of the Institute. It was there somewhat vigorously discussed on both sides. It seems to me that the art has progressed a good deal since that meeting, and the iron tower has become very much more important as a support for transmission lines than it was then. At that time one could consider, for the larger portion, at least of existing plants and perhaps the larger portion of plants then under construction, that the wires were erected upon wooden pole lines with wooden cross-arms, and that one could rely to some considerable degree upon the insulation of the wooden parts supporting the insulators. At the present time one must look upon the future transmission lines, and even the most important transmission lines of the present day as they are being built, as lines supported upon iron towers and therefore lines for which one can only rely upon the insulators themselves to give the insulation. It seems to me that the latter condition, as compared with the old wooden pole lines, makes this discussion of the overhead grounded protective wire quite a different matter. When we had the advantage of the wooden insulation to assist the overhead insulator, anything which brought the potential of the earth closer to the transmission line, as would be the case with the overhead grounded conductor, was inclined to increase the probability of a breakdown of the insulator, for the reason that it reduced the amount of added resistance to breakdown by reducing the length through the wood. I think that that effect has to a large degree been the effect that has led many people to object to the overhead grounded conductor, especially when added to the fact that the overhead grounded conductors were frequently put up very badly and caused trouble on account of their poor mechanical structure. However, even badly put up as they were of old, and notwithstanding the condition by which (with the wood pole line) the breakdown stress after the cloud discharge had occurred was increased on the insulators, the fact that the grounded conductor made a secondary circuit which in a certain extent abates the surges (as was pointed out, I think, by Mr. Steinmetz at the Niagara meeting I refer to), apparently gave the grounded conductor considerable value.

Now, when we come to the situation where the wooden insulation is out of the account, a reduction of perhaps 50 per cent. of the electrostatic stress on the insulator is well worth while, as Mr. R. P. Jackson points out. I doubt whether the reduction in the direct electrostatic stress produced by the grounded wire would be so great as 50 per cent., but if the reduction is as great as 25 per cent., which I have been able to convince myself it might be, I think it might be well worth obtaining in the case of a line built upon iron towers. Perhaps the reason that Mr. R. P. Jackson and myself differ as to the amount of reduction of the stress that comes about by a single overhead grounded wire lies in the fact that he has in his mathematical formulas taken no account of the disturbing influence of the metal line conductors themselves, while I have tried to do that, and when one takes three-phase wires six feet apart and puts a single grounded conductor a few feet above them, the influence is not nearly so great as one would imagine he would obtain from an examination of these equi-potential curves of Mr. R. P. Jackson's paper. This is by no means a criticism of Mr. R. P. Jackson's paper, which I think is a most suggestive paper and which comes at the very pertinent moment when the construction is changing from the old wood pole line construction to the preferable iron tower construction.

D. R. Scholes: I am hardly qualified to speak on this subject, so far as potential stresses are concerned, but I come in contact quite a good deal with the problem of the grounded conductor in building transmission-line towers, and it is interesting to learn how great the range of opinion is regarding the question. In some very long lines using steel towers no overhead grounded wire has been provided. This is true with regard to the lines of the Niagara, Lockport & Ontario Power Company. A certain amount of trouble has been reported with the top insulators in these lines, presumably due to the absence of the overhead grounded conductor. In some cases, one, two, or as many as three overhead grounded wires are provided for in the towers; in other cases there are guards placed over the insulators, or lightning-rods are provided, projecting considerably above the top of the insulator. In one installation now under construction in South Carolina, three overhead grounded wires are installed, placed in a sort of umbrella arrangement over the power wires, which seems to be the most extensive attempt at protection against lightning or static discharges by means of grounded wires that has yet been made.

The usual idea that occurs to the tower builder regarding the effectiveness of the overhead grounded wire is that if it is placed at such elevation that a plane passing through it and making an angle of 45 degrees with the horizontal lies above all the power wires, the power wires will be protected. Where this idea gets its foundation I do not know, but it comes to us very often, and we are often called upon to place the grounded conductor supports in this way. Almost without exception the towers that are now being built, to my knowledge, are provided with ground wire support in such way that if the ground wire is not strung at the outset it may be strung later, if developments indicate that it is needed.

H. C. Hoagland: My experience has been chiefly in Michigan where we have had trouble with lightning. We ran a grounded wire on the under side of the transmission wire, and then noticed that the lightning discharged down to the poles, splitting them. After putting on the ground-wire it practically eliminated that trouble. On the line from Jackson to Battle Creek two ground-wires were used on the top arm, one on each end of the arm, and that practically relieved the trouble in that case. In Illinois a part of the line is equipped with the ground-wire on top of the pole; that has only been in service about a month, but there has been no trouble on that line. On some of the other lines there has been serious trouble; they have been shut down four or five times in the last month. Arrangements are now making to put the ground wire on top of the poles as fast as it can be done. There is only one ground-wire, but on new construction perhaps it would be best to install two ground-wires.

P. M. Lincoln: I would like to ask Mr. Hoagland if his experience has demonstrated that the ground-wire is of positive value in preventing lightning discharges?

H. C. Hoagland: It has been demonstrated beyond any question of doubt in my mind that it is a great benefit even on the wooden poles, as in the Michigan case. We had several cases where four or five poles have been split into slivers. Putting on the ground wire did away with all that trouble.

R. P. Jackson: In regard to putting a lightning-rod on top of the tower. In some cases that feature results for good. Any conductor carried up above the insulator which the lightning may strike if it comes that way and which will also relieve the stress through the space, that is, the electrostatic stress through the atmosphere, will help matters, but it is not a complete relief. I have heard of cases where devices of this kind have been put up and a partial relief obtained, the number of broken insulators was much less, but that number could be still further decreased by putting up grounded lines which would prevent the transmission lines from accumulating such a static charge as they would otherwise. Of course if not released such charges will go to sub-stations and get into the generating stations and transmitting apparatus, but probably they will pass off at the next insulator. The greater the charge the greater the tendency to get off on a near-by insulator.

James Lyman: I was in Montana about a year ago and looked over some of the transmission lines, including the Madison River and the Big Hole transmission line. These transmission lines were put in about six or eight years ago. The Big Hole line is 15,000 volts, two three-phase transmission lines on one pole line. This line is about twenty miles long. It goes over a divide in the mountains where particularly severe discharges take place; these discharges are so severe that when the pole line was built the tops of nearly all the trees showed indications of having been struck. There was some hesitancy about building a pole line there, in fact all sorts of interruptions were expected. To guard against trouble, for three or four miles of this divide a barbed wire was run along the tops of the trees that had been struck by lightning; on each side of the pole line. Three barbed wires were also put on top of the pole line, one on the extreme ends of the upper cross-arm, which also carried one conductor of each of the two transmission lines, and one barbed wire on the top of the pole and grounded the wires at each pole. As an experiment, to see what the effect of these overhead grounded wires was, a small switch was put into each of the ground-wires, at the foot of the poles, so that all of them could be opened during a thunder storm. The lightning arresters were placed in the usual way at each end of the transmission line. The storm effects were watched soon after the transmission was put in, and the discharges of lightning could often be seen coming down to the barbed wire on the tops of the trees, also to the barbed wire on the tops of the pole line. The lightning-arresters were not particularly active; there was not very much going on, and for some six or eight months during the whole season there was no trouble. During one pretty severe storm, the switches on all the grounded wires were opened the entire length, so that the grounded wires were entirely disconnected from the ground, just during one storm. The lightning arresters discharged almost continuously, and there was anxiety lest some of the apparatus should be injured. It was not, however, during this storm, but it was a practical demonstration of the value of these overhead grounded wires. In the rebuilding of the Madison River transmission, which is about 50,000 volts pressure and about sixty miles long, it was planned to have a liberal size grounded wire, grounded every three or four poles, over the whole line, hoping thereby to get as good service there as that on the Big Hole line, which ran through a district where far more severe storms occurred.

From my experience the transmission lines which are protected by overhead grounded wires are more free from troubles than those which are not. Of course lightning-arresters also add greatly to the protection of the system, and I would recommend them in all cases.

P. B. Woodworth: Lightning protection brings to mind an experience I had with barbed wire. We had an equilateral distribution and it became necessary to put up some kind of protection. A single barbed wire was placed above the equilateral triangle. To specify barbed wire is one thing, and to actually put up a barbed wire is quite another thing. After we got it up it apparently worked well. But once—more than once, once in particular that I remember—the wire broke. Stranded barbed wire is usually wound on a reel. When that wire broke it wanted to get back on the reel, and it went round and round those three wires, time and time again, and one can imagine the situation when it became necessary to cut down a barbed wire so located.

W. L. Abbott: If I might be pardoned for introducing a reference to direct-current low-tension matters into this meeting, I will tell of an experience which we had in the Harrison St. power house of the Chicago Edison Company, which at that time supplied direct current only to an underground system.

During one particularly severe thunderstorm we noticed at every flash of lightning a flash at the commutator brushes, and at the instant of this discharge at the brushes the dynamo was so charged that the dynamo tenders would receive severe shocks if they were in contact with the machine, although ordinarily the machine could be handled without any discomfort whatever. During this storm several switchboard instruments grounded to their frames and burned out. We thought at the time that the lightning had struck a building in the city, followed our conductors to the power house, and had gone to ground through the iron framework of the building. We decided afterward, however, that the lightning had struck the iron smokestack of the power house and had finally found a ground by jumping from the framework of the building to the generators and switchboard apparatus, and then again to ground through the underground network.

W. B. Jackson: It has long been the feeling among a large portion of men operating electric transmission lines in regions where severe electrical disturbances occur that well installed grounded conductors when properly placed are a very material protection. Many have figured out reasons for this protective characteristic from a more or less practical standpoint. Mr. R. B. Jackson now presents a careful theoretical analysis of the situation as he sees it. This analysis, coupled with the practical results that appear to have been obtained by use of the grounded conductor, strengthens tremendously the argument in favor of the installation of this class of protection. To-day it seems there is very little that is being undertaken in practice in the field of alternating-current transmission of power that can not be greatly assisted by a careful consideration of the theory. In fact it almost seems that the old time condition is being reversed in these matters and that theory must now "blaze the trail" and practice finish the clearing. The old complaint that grounded conductors are more trouble than good is now a thing of the past, for it is entirely practicable to install properly located and grounded steel wires so that they will give much less trouble than the line they protect.

There is a fine opportunity for study upon electric lines affected by destructive electrical phenomena, by the use of the oscillograph. It would seem that such work when undertaken upon regularly operating lines should have something of the same zest as the photographing of the tiger in its native jungle. In fact it would seem that extreme persistence and patience and courageous endeavor, besides a good deal of experience, would be required to get oscillograph records of all of the phenomena involved. Mr. R. B. Jackson has evidently given this matter of grounded protective conductors careful study, but he has other things that must demand the greater part of his time, and the complete study of this subject is one that may worthily occupy the complete time and attention of careful investigators for an extended period.

This is a splendid subject to be taken up with the assistance of the large income of the Carnegie Institution of Washington, D. C., and one or more of the able scientists of that Institution might execute the work. I suggest that the American Institute of Electrical Engineers throw its influence toward such an end.

George Hayler (by letter): I am much interested in Mr. Jackson's paper. Mr. Jackson, while treating the problem simply from the theoretical standpoint, confirms absolutely our actual experience with high-tension lines.

We have been operating a power system about forty miles long, at 33,000 volts, 25 cycles, for something over two years, and this will be the third season for electrical disturbances.

The original lines were built in the form of an equilateral triangle, with the apex pointing upward, the ground-wire running the entire length of the system, and located about three feet below the cross-arms. This form of construction while exceedingly economical, is, in my opinion, the worst possible arrangement that could be devised. Virtually all of the interruptions to the service, caused by atmospheric disturbances, have resulted from the failure of the top insulators, showing beyond a doubt that the greatest potential strain occurs at that point.

The result in every case has been the same; that is, the top of the pole has burned off, down to the ground-wire. Last year we built five or six miles of line, using a new form of construction. The ground-wire on one line was placed on top of the pole and the conductors arranged on two cross-arms below. In the other case, the ground-wire was placed on one pin of the upper arm. There were numerous storms last season, and so far this year there have been four of more than usual severity. It may be only a fortunate coincidence, but the fact remains that none of these lines have ever caused us the slightest trouble, although we have ample evidence of severe lightning discharges along the route. About two weeks ago one of our employes saw the lightning actually strike a portion of this line about four pole lengths from No. 5 sub-station. The only damage was a punctured high-tension transformer terminal which caused a temporary short-circuit and threw out the circuit-breaker. I am thoroughly convinced that had this discharge taken place in the neighborhood of some of our old lines we should have undoubtedly lost a pole and suffered consequent interruption.

I am pretty thoroughly satisfied from my own experience that the grounded overhead conductor is the only practicable method of preventing insulator trouble due to severe atmospheric disturbances. I believe that the grounded conductor should be of a fairly large cross-section, not less than No. 4 gauge, and preferably stranded. It should be of the very best quality of annealed iron, thoroughly galvanized, and should be grounded at least on every other pole.

It will perhaps be of interest to tell that our type V arresters, as we now have them arranged, are working perfectly, and since their installation we have not lost five cents' worth of apparatus due to the failure of the protective devices. There is a slight tendency for the cylinders to weld together under a very severe discharge, but careful inspection will prevent any serious trouble arising from this cause, since it is our experience that very seldom do a sufficient number of cylinders weld together during one discharge to cause a breaking down of the arresters at normal potential.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1907.

The Board of Directors presents herewith for the information of the INSTITUTE a report of its work during the year, and of the various standing and special committees, also the financial standing of the organization.

The Annual Convention was held at Milwaukee, Wisconsin, May 28-31. The total registered attendance was 236. At this convention President Wheeler delivered his annual address upon the subject of Engineering Honor, and twenty professional papers were read and discussed, also the report of the Standardization Committee.

The Board of Directors has held nine monthly meetings during the year, and the Executive Committee one meeting.

In response to the invitation of the Institution of Electrical Engineers, a representative party from the American Institute of Electrical Engineers was organized to meet with European electrical engineers at London, June 24, 1906, and join with them as guests of the Institution in a circular tour through Great Britain. The Board of Directors was represented on this tour by President Wheeler, Past President Lieb, Manager C. O. Mailloux and the Secretary. There were in the party 23 Members and 12 guests from America, and 22 Members and 6 guests from foreign countries. An official banquet was given in honor of the visitors, at Hotel Cecil, June 25, at which about 500 guests were present. After devoting three days to various technical visits in London and vicinity, the party started June 28 on the circular tour, which included visits to Stratford, Rugby, Birmingham, Manchester, Liverpool, Glasgow, Edinburgh, Newcastle-on-Tyne, Leeds and Harrogate. This trip was made on a special train of dining coaches furnished by the London and Northwestern Railway. Every detail was successfully carried out, and the entire tour was not only instructive, but thorougly enjoyable in every respect.

Board of Examiners.—Ten meetings were held during the year, at which applications for election as Associates, enrolment as students, and transfer to the grade of Member have been reported to the Board of Directors as follows:

Recommended for election as Associates	944
Not recommended for election as Associates	4
Recommended for enrolment as students	459
Recommended for transfer to grade of Member	40
Not recommended for transfer to grade of Member	9
Reinstated to grade of Member	1
Held for further information	7
Total applications considered	1,464

Local Organization Committee.—This committee reports a present total of 33 local organizations included under the heads of Branches, University Branches and Student Meetings. The University of Illinois has been made a regular Branch by the Board, it having the requisite number of Members and Associates required by the By-laws. Student Meetings have also been authorized by the Board at the University of Maine and the Montana Agricultural College. A design for a student's pin has been authorized, and a supply ordered for sale. A conference with the Editing Committee led to an arrangement for the publication of meritorious original papers emanating from the Branches. There have been over two hundred Branch meetings held, with a total attendance of 16,500. At these meetings 137 original papers have been presented. Cornell shows an average attendance of 130, with a maximum of 225, Purdue an average of 100, with a maximum of 265, Wisconsin an average of 60, with a maximum of 175. All of the University Branches show that the enrolled Students are taking an active interest in the work. As soon as the revenue of the INSTITUTE will permit, it is the general belief that arrangements should be made for the systematic visitation of Branches by officers of the INSTITUTE and prominent engineers. There is a general call for some action of this kind which it is hoped would be productive in general good fellowship. The encouragement of the attendance of delegates from the Branches to the Annual Convention is also recommended by the committee.

The Engineers' Building.—During the past year, the permanent home of the INSTITUTE, occupied jointly with the American Institute of Mining Engineers and the American Society of Mechanical Engineers, has been finished and officially dedicated. Through the medium of the United Engineering Society, as a holding corporation, the American Institute of Electrical Engineers is the owner in perpetuity of one third of the property numbers 25, 27, 29, 31 and 33 West Thirty-ninth Street, being five city lots, valued at $540,000, purchased by members and friends of the societies, and the building thereon, erected at a cost of $1,050,000, which was the gift of Andrew Carnegie to the founder societies. The corner stone was laid by Mrs. Carnegie, May 8, 1906, when the structure was well advanced. The first INSTITUTE meeting was held in the Auditorium, January 25, 1907, and the offices of the INSTITUTE were occupied February 4, 1907. Inasmuch as the INSTITUTE has acquired a one-third interest in the Engineers' Building, the value of the equity therein has been included as an asset, and appears for the first time in the financial statement.

Building Fund Committee.—The last annual report of the Building Fund Committee stated that on April 30, 1906, the subscriptions had reached a total of $132,434.30 from 644 subscribers, and that $88,238.10 had been received and deposited in the Treasury of the INSTITUTE. The Committee reports that at the same date this year the number of subscribers to the fund had risen to 934; that the amount subscribed had reached $163,734.47, and that the amount actually collected and deposited had reached $124,829.17. It will be seen, therefore, that the new subscriptions during the year reached over $31,000, and that the cash collections during the year amounted to $36,591. The largest contributors during the year were Mr. George Westinghouse and the associated Westinghouse Companies; namely, the Westinghouse Electric and Manufacturing Company; the Westinghouse Air Brake Company; the Westinghouse Machine Company; Westinghouse, Church, Kerr Company; the Union Switch and Signal Company; the Nernst Lamp Company, and the Cooper Hewitt Electric Company. These interests subscribed the munificent sum of $50,000 toward the Building Fund of the three founder societies, and the INSTITUTE received one-third of this amount. The INSTITUTE also received one-third of a similar subscription of $3,500 made by the Allis-Chalmers Company. One of the most encouraging features of the work of the year was the large increase in subscriptions for moderate sums from individual members of the INSTITUTE, nearly 300 names being added to the list. It will be seen that barely $20,000 is now required to complete the amount that the INSTITUTE wishes to collect in order to meet its obligations in this respect, and it is believed that as there are still some 75 per cent. of the members who have not contributed to this fund this amount shall be pledged during the present year. At the same time, it may be pointed out that with nearly 1,000 subscribers to the fund, the Land and Building Committee is able to report a larger percentage of subscriptions from membership than has ever been secured before in this country in work of the same character in a technical society.

Standardization Committee.—A preliminary report prepared by this committee was presented at the Milwaukee Convention in 1906, where it was very thoroughly discussed, and referred back to the committee for further revision before being submitted to the membership.

The committee has held eleven meetings during the year, and the amended rules have been sent out to such members of the INSTITUTE as were believed to be especially interested in the work. A large number of suggestions have been received, many of which were incorporated in the tentative draft, and the rules are now practically in suitable form to be resubmitted for consideration at the Niagara Falls Convention.

Committee on Bibliography.—By the terms of the Wheeler Deed of Gift, dated May 17, 1901, conveying to the INSTITUTE the Latimer Clark library, a complete catalogue *raisonne* is to be published in the name of the INSTITUTE, reciting the condition of gift and explaining the features of interest of each book, for the convenience and information of members. The preparation of these entries, their verification, and chronological and subject classification, has been completed, and the work is now in the hands of the printer. Arrangements have been made with the Library of Congress and the British Museum for a careful comparative reading of the proofs, and Dr. Silvanus P. Thompson, Dr. G. Hellman and Paul F. Mottelay have also kindly consented to read them critically. The necessary care required to insure accuracy, and render the work authoritative and worthy of the INSTITUTE, involves a considerable amount of time, but it is hoped that the volume will be finished during the present year.

Committee on Papers.—This committee has endeavored to obtain theoretical and practical papers covering the principal branches of the art, and also to make the discussions more valuable, by inviting specialists to take part, after studying the papers in advance. Sixteen papers were presented at New York, and 21 are listed for the Annual Convention at Niagara Falls, in addition to topical discussions.

The committee recommends the preparation of rules and specifications for the guidance of authors in order that suitable cuts may be prepared for publication at a considerable reduction in cost.

The Editing Committee.—Immediately after its appointment, the attention of this committee was directed to the possibility of making the Proceedings a vehicle of information to the membership, of the general work of the INSTITUTE. A conference with the Local Organization Committee brought out the desirability of also including therein a larger proportion of meritorious papers originating through the Branch meetings. This work was undertaken beginning with the October 1906 issue, and many expressions of approval have reached the committee and the Secretary. The change has involved considerable additional labor and expense, but the result has not only been appreciated by the membership, but has made the Proceedings a still more valuable advertising medium.

John Fritz Medal.—On the occasion of the dedication of the Engineers' Building, April 17, 1907, this medal was presented to Alexander Graham Bell, Past-president of the Institute, in accordance with the decision of the John Fritz Medal Board of Award, upon which the INSTITUTE is represented.

Committee on Law.—The attention of this committee has been again devoted to a revision of the Constitution. The failure in the adoption of the draft submitted a year ago, led to the preparation of a revision embodying fewer changes, and the committee had the benefit of the advice of a majority of its members representing the interests of the Branches. The result was satisfactory in enlisting the enthusiastic support of the Branches, many of which made special efforts to induce their members to send in their votes, with such success that over 2,500 ballots have been received.

High Tension Transmission.—A specia meeting was held in New York, March 22, under the auspices of this committee, at which introductions to discussions had been prepared. In addition to the oral discussion, a large number of written contributions were received from members in various parts of the world. The committee has arranged for another meeting at Chicago, May 24, and for a session at the Niagara Falls Convention. Arrangements were made for the publication in a single volume of the earlier work of this committee, the sale of which was very satisfactory, and a second edition is now being printed. The royalties received for these publications will practically cover the expenses of the committee, while the direct professional value of the information thus obtained and disseminated, is strong evidence of the benefits to be derived from the work of the INSTITUTE.

Increase of Membership.—This committee has been continuously occupied during the year in bringing to the attention of non-members actively engaged in electrical work, the increasing prestige of the INSTITUTE in order that its benefits and usefulness might be more generally appreciated. The results have been very gratifying, as shown by the number of candidates posted each month, reaching a total of about 1,200 during the period covered by the work of this committee. Since January 1, about 40 enrolled students have applied for election as Associates. The cost of carrying on the work of this committee is estimated at about one dollar for each application received.

Membership.—The total membership at the close of last year's report was 3870 classified as follows:

Honorary Members		2
Members		508
Associates		3360
Total May 1, 1906		3870
Elected prior to May 1, 1906, and since qualified		90
Elected May 1, 1906, to April 30, 1907, and qualified		751
Restored to Membership		1
		4712
Deduct—		
Total Deaths	22	
Total Resignations	40	
Dropped as delinquent	129	
		191
Total membership April 30, 1907		4521

The membership April 30, 1907, is classified as follows:

Honorary Members	2
Members	536
Associates	3983
Total	4521

Associates Elected.—The Associates elected during the year, May 1, 1906, to April 30, 1907, and their present status is as follows:

Qualified and now Associates	751
Elections cancelled	2
Not qualified on April 30	196
Total elections	949

Resignations.—The following Members and Associates have resigned in good standing during the year:

Members.—A. E. Childs, P. Dawson.

Associates.—W. Ambler, F. F. Bahnson, S. R. Barton, G. R. Bott, W. F. Bouché, Orion Brooks, E. M. Burgess, H. S. Burroughs, E. L. Caldwell, F. R. Chambers, R. E. Cunningham, C. C. Curtis, W. H. Dopp, C. A. Fernald, George S. Gibbs, J. M. Gilmore, Phillip Hamlin, W. E. Hopton, C. E. Harthan, M. C. Hull, J. E. H. Hyde, J. E. Ives, P. H. Lombard, W. K. Leggett, Felix Levy, John Lind, W. W. Mason, Jr., J. A. L. Möller, G. E. McCarn, W. E. Moody, G. W. Nistle, F. R. School-field, A. V. Sedgwick, R. C. Shaal, Angus Sinclair, F. S. Stitt F. R. Spiller, C. H. Tyndall. Total, 40.

Deaths.—There have been during the year the following deaths:

Members.—A. V. Abbott, J. B. Cahoon, F. L. Freeman, Eugene Griffin, F. E. Jackson, J. E. Lloyd.

Associates.—C. A. Bragg, Louis Cassier, E. E. Davis, K. G. Gillberg, H. W. Goode, A. E. Hayes, W. C. Johnson, W. J. Johnston, B. E. Mercil, K. Okamota, C. F. Parker, C. L. Spier, A. H. H. Trott, F. Townsend, L. C. Whitehouse, W. A. Whittlesey. Total, 22.

Dropped as delinquent during the year, 129.

The average receipts and disbursements *per capita* for the past seven years, are shown in the following table:

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past seven years.

Year	1901	1902	1903	1904	1905	1906	1907
Membership, April 30th, each year	1260	1549	2230	3027	3460	3870	4521
RECEIPTS PER MEMBER:							
Entrance Fees	$0.61	$1.16	$1.59	$1.65	$0.83	$0.75	$0.90
Dues	8.61	10.06	9.01	9.33	9.30	9.47	8.95
Transactions, Sales, Advertising	1.03	1.54	1.79	2.11	1.70	2.15	1.81
Badges	.18	.26	.35	.39	.28	.27	.30
Interest	.12	.24	.21	.18	.21	.13	.25
	$10.55	$13.26	$12.95	$13.66	$12.32	$12.77	$12.21
DISBURSEMENTS PER MEMBER:							
Transactions	$2.83	$3.50	$4.67	$3.43	$3.77	$3.33	$2.83
Salaries	2.49	2.78	2.49	2.50	2.20	2.64	2.53
Meeting Expenses, incl. Branches	1.05	1.13	.87	1.16	.82	.68	.68
Housing	.94	.94	.65	.79	.75	.68	1.33
Library, incl. Rent and Salaries	.55	1.85	1.38	1.39	.81	.69	1.37
Postage	.46	.51	.69	.66	.66	.58	.59
Stationery and Miscel. Printing	.39	.53	.96	1.01	.70	.78	.85
General Expenses	.33	.59	.52	.45	.54	.29	.43
Badges	.16	.19	.27	.35	.25	.22	.29
Express	.15	.15	.15	.28	.22	.23	.28
Advertising						.36	.30
Office Fittings							.14
Total	$9.35	$12.17	$12.65	$12.02	$10.72	$10.48	$11.62
Credit Balance per Member	$1.20	$1.09	$0.30	$1.64	$1.60	$2.29	.59

LAND, BUILDING AND ENDOWMENT FUND.

RECEIPTS.		DISBURSEMENTS.	
Before appointment of Committee	$ 6,100.00	Paid United Engineering Society, acct. Contract	$ 8,000.00
Collected by Committee	123,361.67	Paid United Engineering Society, acct. Mortgage	9,000.00
Interest on balances	2,910.38	Paid United Engineering Society, acct. Interest	10,620.00
		Paid for Fittings and Furniture of Engineers' Building	3,924.04
		Expenses of Committee	4,681.94
		Balance in bank May 1, 1907	96,146.07
	$132,372.05		132,372.05

NOTE:—

Collected by Committee, as reported above	$123,361.67
Collected by Committee deposited since May 1	1,467.50
Total collected by Committee as per the Committee's report	124,829.17

New York, May 20, 1907.

Dr. Samuel Sheldon,
President of the American Institute of Electrical Engineers.

Sir: Pursuant to the provisions of the Constitution, the Committee on Finance has during the year exercised supervision over the financial affairs of the Institute. It has considered all bills and approved for payment such as constituted a proper charge against the Institute.

It has considered and reported upon specific appropriations, and has made special reports upon various matters referred to it by the Board of Directors.

As provided by the Constitution, it has employed an expert accountant to audit and report upon the accounts of the Institute; and this report made by Messrs. Peirce, Gimson and Co., certified public accountants, has been approved by the Committee on Finance, and is transmitted herewith.

Very truly yours,
J. J. Carty,
Chairman Committee on Finance.

GENERAL FINANCIAL STATEMENT.

Mr. John J. Carty,
Chairman Committee on Finance.

Sir: In accordance with your instructions, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1907.

The results of this examination are presented in four exhibits, attached hereto, as follows:

Exhibit A. Balance sheet April 30, 1907.

Exhibit B. Receipts and disbursements for general purposes for year ended April 30, 1907.

Exhibit C. Receipts and donations for designated purposes, also expenditures on same for year ended April 30, 1907.

Exhibit D. Condensed cash statement.

We beg to present attached hereto our certificate to the aforesaid exhibits.

Yours very truly,
Peirce, Gimson & Co.,
Certified Public Accountants.

Mr. John J. Carty,
Chairman Committee on Finance.

Dear *Sir*:

Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1907, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30, 1907, and that the accompanying statements of Cash Receipts and Disbursements are correct.

Peirce, Gimson & Co.,
Certified Public Accountants.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Balance Sheet April 30, 1907.

Exhibit A.

Assets.

Cash:		
Land, Building and Endowment fund	$96,146.07	
Carnegie (Library) fund	3,529.60	
General Library fund	237.00	
Compounded Membership fund and Interest	5,465.34	
*Mailloux fund	1,007.55	
International Electrical Congress of St. Louis, 1904, Library fund	2,140.10	
	$108,525.66	
*General cash in bank	17,624.24	
Secretary's petty cash on hand	500.00	$126,649 90
United States Government Bonds 3s, 1918	8,000.00	
Premium on Bonds	320.00	
		8,320.00
Equity in Societies Building (25 to 33 West 39th Street)	350,000.00	
One-third cost of land (25 to 33 West 39th Street)	180,000.00	
		530,000.00
Library volumes and fixtures	24,174.76	
Transactions	4,352.75	
Office furniture and fixtures	5,114.30	
Works of art, paintings, etc	2,300.00	
Badges	210.25	
		36,152.06
Accounts Receivable:		
Members for past dues	8,966.60	
Members for entrance fees	295.00	
	9,261.60	
Miscellaneous	145.60	
Subscriptions	24.90	
For advertising	1,661.47	
		11,093.57
United Engineering Society, assessment, advance payment May and June		2,222.22
Total Assets		714,437.75

* The Farmers' Loan and Trust Co. deposit account includes $7.55 of the Mailloux Fund.

Liabilities and Surplus.

Funds:		
Land, Building and Endowment Fund	$96,146.07	
Carnegie (Library) Fund	3,529.60	
General Library Fund	237.00	
Compounded Membership Fund and interest	5,465.34	
Mailloux Fund	1,007.55	
International Electrical Congress of St. Louis, 1904, Library Fund	2,140.10	
	$108,525.66	
Reserve fund (U. S. Govt. Bonds)	8,320.00	
Total		$116,845.66
United Engineering Society (for cost of land)		171,000.00
Total liabilities		$287,845.66
Surplus:		
In cash	$18,124.24	
In property and accounts receivable	408,467.85	
		426,592.09
Total liabilities and surplus		$714,437.75

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DISBURSEMENTS FOR GENERAL PURPOSES FOR YEAR ENDED APRIL 30, 1907.

EXHIBIT B.

RECEIPTS.		
Entrance Fees	$4,075.00	
Current Dues	35,653.25	
Past Dues	2,310.00	
Advance Dues	219.00	
Students' Dues	2,256.00	
Transfer Fees	395.00	
Badges	1,367.50	
		$46,275.75
Sales, Transactions	915.07	
Subscriptions, Proceedings	661.98	
Advertising	5,597.35	
Binding	89.80	
Exchange	14.59	
INTEREST:		
U. S. Govt. Bonds	240.00	
Bank Balances	865.10	
Royalty	239.75	
Sundries (refund)	13.32	
Insurance Rebates	22.13	
Rent (sub-tenant)	250.00	
		8,909.09
Total		$55,184.84

DISBURSEMENTS.		
Stationery and Printing	$3,830.80	
Postage	2,669.83	
General Expenses	1,972.26	
Meeting Expenses	1,861.13	
Branch Meetings	1,196.96	
Badges	1,354.30	
Salaries	9,407.40	
Rent	2,645.04	
Office Furniture	652.39	
		$25,590.11
PROCEEDINGS—TRANSACTIONS:		
Printing	6,624.79	
Salary	2,000.00	
Engraving	1,446.97	
Volumes	3,299.32	
Electrotyping	689.29	
Binding	704.79	
Express	1,272.76	
Advertising Commissions	1,380.00	
		$17,417.92
LIBRARY:		
Rent	1,475.04	
Librarian salaries	887.20	
Library Insurance	106.35	
Miscellaneous	395.66	
		2,864.25
United Engineering Society		6,666.66
Total		$52,538.94
Excess receipts over disbursements deposited in general fund		2,645.90
		$55,184.84

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES ALSO EXPENDITURES FOR YEAR ENDED APRIL 30, 1907.

EXHIBIT C.

RECEIPTS.	
Land, Building and Endowment fund, Donations, Interest, etc	$37,062.46
Carnegie (Library) Fund, Interest	119.08
General Library Fund, Interest	7.08
Life Membership Fund	578.37
International Electrical Congress of St. Louis, 1904, Library Fund	73.04
Mailloux Fund, Interest	30.00
Total	$37,870.03
EXPENDITURES.	
Land, Building and Endowment Fund	$21,617.01
Carnegie (Library) Fund	541.85
General Library Fund	2.64
Mailloux Fund	23.20
Total Expenditures	$22,184.70
Deposited to credit of their respective fund accounts	15,685.33
Total	$37,870.03

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Condensed Cash Statement.

Exhibit D.

Cash on deposit April 30th, 1906	$107,818.67	
Secretary's petty cash April 30th, 1906	500.00	
	$108,318.67	
Receipts for general purposes, Exhibit " B "	55,184.84	
Receipts for designated purposes, Exhibit " C "	37,870.03	$201,373.54
Disbursements for general purposes, Exhibit " B "	$52,538.94	
Expenditures for designated purposes, Exhibit " C "	22,184.70	
		$74,723.64
Balance on hand April 30th, 1907		$126,649.90
On deposit for designated purposes, Exhibit " A "	$108,525.66	
On deposit for general purposes, Exhibit " A "	17,624.24	
Secretary's petty cash, Exhibit " A "	500.00	
		$126,649.90

PROPERTY ACQUIRED DURING THE YEAR.

(Reported as directed by the Constitution.)

Office Furniture and Fixtures	$4328.86
Library Books and Binding	500.00
Engineering Societies Building, Equity	350,000.00

All outstanding bills rendered prior to May 1st, 1907, have been paid.

Respectfully submitted for the Board of Directors.

Ralph W. Pope, *Secretary.*

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF LIBRARY COMMITTEE

In accordance with the provisions of the Constitution, we present the following report of the more important features of history of the Library of the Institute for the year ending April 30, 1907; the present condition of the several funds from which the support of the Library is directly derived; its present status as one of the associated libraries in the new Engineering Societies Building; and plans for the future.

RECENT SLOW GROWTH

During the past four years the overshadowing activity in securing by subscription the fund to purchase the land for the new building, and the labor attending its construction and equipment have naturally and properly occupied the minds and time of the active members of the Institute to an extent which has prevented such rapid progress of the Library as was recorded in the report of May 1, 1903.

It should, however, be noted that even under these unusual circumstances and amid these extraordinary calls upon the interest and resources of the members and friends of the Institute, the Library has in the past four years increased in number of volumes (not including duplicates) from 7727 to 10577, a gain of 2850 volumes; and in valuation of volumes from $16211.10 to $21726.47, a gain of $5515.37. This increase of over 35 per cent. in number of volumes is gratifying as indicating what may hereafter be accomplished now that the Library has a permanent fireproof home, offers greatly increased conveniences, and is in other ways richly deserving of the cordial support of a rapidly growing number of members and friends of the Institute.

GIFTS OF BOOKS

During the past year Mr. Edward D. Adams has once more illustrated the practical value of his support of the Institute Library by contributing a collection of about 200 scientific books, a list of which appeared in the October issue of the PROCEEDINGS.

Similarly, the McGraw Publishing Company has donated about 25 of its recent publications, which supply in part the serious need of the latest editions of electrical text-books, and new publications of the same character. The same Company has also turned over to the Institute a large collection of unbound electrical patents issued in this country during the past 15 or 20 years.

Another and very complete collection of United States electrical patents issued from the early years down to about 1904 has just been donated by Messrs. Dyer and Dyer. This will prove specially important in the equipment of the headquarters of some progressive Institute Branch.

The complete list of donors for the year is as follows:

ADAMS, E. D.
ALLEGEMEINE ELEKTRICITATS GESELLSCHAFT
ALLEN, W. F.
AMERICAN RAILWAY ASSOCIATION
CANFIELD, DR. JAMES W.
CARROLL, WM.
CARTY, J. J.
M. LE DIRECTEUR CONSERVATEUR NATUREL DES ARTS ET METIERS
CROCKER, F. B.
DUNBAR, JAMES W.
DYER AND DYER
L'ECLAIRAGE ELECTRIQUE
GERARD, LEON
GAUTHIER, VILARS
HAMACEK, ADOLPH F.
HAMMOND, ROBERT
INSTITUTION OF ELECTRICAL ENGINEERS
JENKS, W. J.
LIBRARY OF CONGRESS
MCGRAW PUBLISHING CO.
MARTIN, T. C.
MASS. BOARD OF GAS AND ELECTRIC LIGHT COMMISSIONERS
MULOCK, SIR WM.
NEW YORK CITY COMMISSION ON ELECTRIC LIGHT
PEDERSON, F. M.
PLASS, J.
RIES, E. E.
ROBERTSON, LESLIE S.
ROSENTHAL, S. W.
SHELDON, DR. SAMUEL
SHEPARDSON, PROF. GEO. D.
SOCIETY OF ARTS
SWENSON, BERNARD V.
TALBOTT, FRANK
TALTAVALL, T. R.
VAIL, J. H.
WARD, GEO. G.
WEAVER, WM. D.
WHEELER, SCHUYLER S.

STATISTICS OF LIBRARY, MAY 1, 1907.

Source	Titles	Volumes	Pamphlets	Valuation
Report of May 1, 1906	7400	10717	515	$22,060.31
PURCHASES:				
Carnegie Fund				
Donation Fund	7	18		22.45
Mailloux Fund	4	6		23.20
Institute Appropriation	3	6		26.00
Periodicals	25	58		116.00
GIFTS:				
Edward D. Adams	162	300		168.00
McGraw Publishing Co.	23	23		41.25
Miscellaneous	25	58	50	85.00
Gross Totals, May 1, 1907	7649	11183	565	$22,551.21
Duplicates	308	609		824.74
Net Totals, May 1, 1907	7341	10577	565	$21,726.47

In the following table of total valuation of the Library, May 1, 1907, the furniture and cases are those brought from the old offices at 95 Liberty street, no account being included of the new furniture, stacks, etc,.

provided as a part of the initial equipment of the Engineering Societies Building:

TOTAL VALUATION

Books	$22,551.21
Stacks	1,470.25
Furniture, catalogues, cases, etc.	208.28
	$24,229.74

The following tabulations give the state of the four funds from which the Library Committee is entitled to draw:

DONATIONS (GENERAL LIBRARY FUND)

Dr.		Cr.	
Balance May 1, 1906	$232.56	Purchase of books	$ 2.64
Interest May 1, 1907	7.08	Unexpended	237.00
	$239.64		$239.64

CARNEGIE FUND

Dr.		Cr.	
Balance May 1, 1906	$3952.37	Wheeler Bibliography	$ 541.85
Interest May 1, 1907	119.08	Unexpended	3529.60
	$4071.45		$4071.45

MAILLOUX ENDOWMENT FUND ($1,000)
(Proceeds for the maintenance of certain sets of periodical publications)

Dr.		Cr.	
Balance May 1, 1906	$ .75	Subscription	$23.20
Interest May 1, 1907	30.00	Unexpended	7.55
	$30.75		$30.75

INTERNATIONAL ELEC. CONGRESS OF ST. LOUIS, 1904, FUND ($2,140.10.)
(Proceeds for the purchase of international electrical literature)

Dr.		Cr.	
May 1, 1907	$42.54	Unexpended	$42.54

In conformity with Section 33 of the By-laws, this Committee submitted to the Board of Directors at its meeting of October last an estimate of requirements for the year commencing Nov. 1, 1906. The appropriation which resulted is stated below. Pursuant to Section 37, the expenses for the year commencing May 1, 1906, are stated on the other side of the account. This is in accordance with the method pursued in prior reports of this Committee although the actual unexpended balance of the present appropriation year, remaining after six months of operation to the credit of this Committee, with which to meet bills not yet received and the expenses of the coming six months beginning May 1, 1907, is $1582.14 instead of the amount represented by the apparently unexpended balance for the year ending April 30, found in the appended statement.

The charge for rent is calculated for the past year at the rate paid by the Library at the former quarters, from which removal took place about Feb. 1, 1907.

INSTITUTE APPROPRIATION ACCOUNT

Dr.		Cr.	
Appropriation for Maintenance for year ending October 31, 1907	$3363.00	Rent	$1475.04
		Insurance	106.35
		Salary, Librarian	713.20
		" Assistant	174.00
		Building	135.05
		Supplies	7.95
		Subscriptions	26.00
		Express and Postage	8.80
		Books	27.73
		Fixtures	73.08
		Miscellaneous	117.05
		Unexpended	498.75
	$3363.00		$3363.00

THE MOST URGENT NEED

is that of modern text-books to meet the everyday necessities of the patrons of the Library. Only a moderate percentage of the standard works of the past twenty-five years are now on our shelves. A notable opportunity is now presented to some member or friend of the Institute, or several acting together, to contribute a relatively moderate amount for this special object, which has never before assumed anything like its present importance; particularly in view of the fact that the use of this Library is now offered to the public and to nearly 10,000 members of the two founder societies which have now become associates of the Institute in the new headquarters, as will be explained more in detail at the end of this report.

BIBLIOGRAPHY OF THE WHEELER GIFT

The work of digesting the entire Wheeler Gift and preparing the Bibliography for the printer, which has been progressing for five years in the hands of Brother Potamian, is still going forward under the management of W. D. Weaver, who was appointed this year a special committee to complete the task to which he has given so much time and thought since Past-president Wheeler presented the collection to the Institute. Thus the loss which was felt in Mr. Weaver's resignation of leadership in Library affairs, after so many years of most painstaking labor, often at great personal inconvenience and always marked with characteristic grasp of detail and assumption of the entire load of committee responsibility, has been mitigated by his willingness to retain the direction of this important publication, for which funds were provided by Mr. Carnegie. Instead of being restricted to the 1400 members who formed the Institute in 1901, this octavo volume of probably 500 pages, affording annotations to all of the more important books and pamphlets in the collection, will be offered, during the coming fiscal year, to about 4500 members who make up the Institute of to-day; while many Libraries, scientists and engineers outside the Institute will doubtless secure copies at some reasonable price.

HISTORICAL MUSEUM

This is a new development naturally closely affiliated with the Library and merging into it by insensible degrees.

The first effective effort in this direction was made by Past-president

Wheeler shortly before his retirement from office last year, by enlisting the sympathetic coöperation of Mr. Edward D. Adams and then securing the adoption by the Board of Directors, of a general resolution, followed in January by a more specific authorization best expressed in the language of the resolutions then adopted:

> "Resolved, That the Library Committee is hereby authorized to accept on behalf of the Institute, donations of original apparatus, models, photographs, manuscripts printed documents, and similar exhibits, suitable for a museum of historical electrical material; also to accept the loan of material of the same general character which cannot be secured by gift.
>
> "Resolved, That each donation or loan accepted under the foregoing resolution shall be acknowledged by the Chairman of the Library Committee, specifying the articles received in sufficient detail to ensure subsequent identification, and reciting the conditions of gift or loan and acceptance."

The Board also appropriated $200 for the purchase of such cases, frames, etc., as might be desirable for making a start in this direction.

The first donation, by Mr. Adams, was an elaborate and costly model, some four feet in length, of the high-speed three-phase electric railway motor car which was operated on the Berlin-Zossen Railway, in 1903, at a speed of more than 150 kilometres per hour. Offers of early lamps, dynamos, regulators, etc., have been made by Messrs. James J. Wood of Fort Wayne, W. S. Andrews of Schenectady, A. J. Wurts of Pittsburg, Rudolph M. Hunter of Philadelphia, and a few others.

The Committee now invites correspondence regarding original relics, of the general character specified by the resolutions, which can be identified as genuine, and having a well-authenticated history; in other words, " first things " in electrical apparatus, pictures and manuscripts. It is not desired to secure models or papers simply because they are old. To adopt such a course would evidently result principally in establishing an electrical junk-shop. The purpose is to place the Museum at the outset on a high plane of excellence, by judicious selection of available material even though the collection grow slowly; by the exercise of special diligence in gathering and displaying information as to the detail of history which each exhibit represents; and by the provision of adequate protection during many years to come for each accepted article. Thus the conditions of security, permanency, and accessibility which invite contributions to the Library will equally encourage similar donations to the Museum.

Each article or group accepted will bear the name of the donor, and a careful registry will be kept of the conditions, if any, under which it has been contributed; to the end that the wishes of the donor regarding it may be kept in mind and respected by the Institute, in general accordance with the methods pursued in the case of articles donated to other corporate bodies, such as the Metropolitan Museum of Art.

Sub-committees

The unusual number and importance of the tasks devolving upon this Committee this past year have been lightened by a division of labor indicated by the duties of four sub-committees, as follows:

(1) Purchase of furniture and floor covering for Institute offices: Edward Caldwell, Frank N. Waterman.

(2) Library subscriptions, purchases and donations: Edward Caldwell, C. A. Terry.

(3) Increased Library utility: Professor Charles F. Chandler, C. A. Terry.

(4) Historical Museum: F. N. Waterman, W. J. Jenks.

Much consideration has been and will be given to devising and putting into practice plans for enabling members at a distance, who cannot consult this Library in person, to secure many benefits from a liberal equipment and maintenance. It is proposed to offer facilities for getting certified excerpts from rare volumes, photographs of pages and diagrams, or translations from several foreign languages, all at a moderate charge; also to loan duplicate volumes under suitable restrictions. Correspondence is especially invited on this question of "increased Library utility."

REMOVAL TO PERMANENT QUARTERS

The completion and opening about January 1 of the new Engineering Societies Building, with its two spacious and convenient floors devoted respectively to reading room and stack room accommodations for the assembled libraries of the three founder societies, invited speedy removal from the extremely contracted and inadequate quarters at 95 Liberty street. This was accomplished in February without the loss or injury of a single volume belonging to the Institute Library. The transfer of the stacks to their permanent location necessitated entire rearrangement and a different system of mechanical support. Thus this transfer required much more time than the mere moving of the books, but everything was completed and the books carefully arranged early in April, and our section of the comfortable and well-lighted stack-room has been made fully available.

THE ASSOCIATED LIBRARIES

Thus far this report has dealt with the Electrical Engineers' Library as an institution by itself. There remain to be considered its relations to its newly associated libraries, and changes in administration which are required in consequence.

The formal dedication of the building, April 16 and 17, found the three libraries of the founder societies occupying their permanent home in coöperative arrangement, offering to the student an aggregate of about 35,000 volumes at the outset, each section in charge of its own librarian, but open primarily to any one of the 15,000 members of all the separate societies, and incidentally to engineering readers generally, outside the fraternity.

The books of the Institute now occupy exclusively two sections or alcoves of the reading room, and also, jointly with the other societies, two other alcoves; thus displaying on the thirteenth floor about one-third of its volumes. The main body of the ancient treasures of the Wheeler Gift, Latimer-Clark Collection, is suitably and securely housed in glass-front wire-protected cases in the stack-room, a few of the most precious books being displayed to the visitor in locked show-cases, with explanatory cards across the open pages. It is the purpose of the Committee to increase the number of these valuable volumes thus shown, as soon as permanent show-cases can be made.

By authorization of the Board of Directors of each of the three founder societies, the chairmen of their respective Library Committees are empowered to meet in conference and jointly direct the mutual relations which now exist. Messrs. Raymond of the Mining Engineers, Suplee of the Mechanical Engineers, and the Chairman of this Committee have thus conferred and agreed upon several tentative conditions of coöperative action and rules of administration. Of these the following are of general interest:

"That no questions shall be decided by majority votes of the three representatives of the three societies, but that all decisions must be unanimous in order to become effective; dissent on the part of any one representative being sufficient to require a reference to the respective library committees, and ultimately if necessary, to the governing bodies of the respective societies, excepting as to matters regarding which the regular single representative is clothed with full powers.

"That for the present, all consideration of the question of a new organization for the administration of the three libraries, or of the appointment of any additional or general librarian, shall be postponed.

"That the present arrangement, under which the three present society librarians administer the three libraries, each under the supervision of her authorized society-representative, and in mutual coöperation as to matters of common interest or necessity, be continued.

"That the Reading Room be open on all week-days, from 9 a.m. to 5 p.m. Only members of the three founder societies, and others duly introduced by the Secretary or other authorized officer of one of the societies, will be permitted access to the alcoves or other spaces inside the rail.

"That for the protection and convenience of members, the Secretary of each society, will, upon application, issue to any member of his society in good standing a personal, non-transferable card, entitling him to the use of the libraries in the alcoves of the Reading Room. This card must be signed by the person receiving it, and surrendered at the desk at the time of its presentation. At every visit he must identify himself by signing his name in the registry.

"That non-members may, in the two outer alcoves, receive and consult books for which they call at the desk; or they may, on similar application to one of the secretaries, secure special cards admitting them to the inner alcoves under similar restrictions.

"The librarians shall have no discretion in the matter of allowing any catalogued pamphlet or volume to be taken from either of the libraries for any purpose, but shall decline to permit any such loan unless authorized in writing so to do by the Chairman of the Committee or the Secretary of the society to which the pamphlet or volume belongs. But a duplicate may be thus loaned at the discretion of the Librarian directly responsible."

LIBRARIANS AND SPECIAL SERVICES

The resignation of Miss Josephine T. Bragg after several years of service as Librarian, resulted in the engagement of Miss Jessie R. Hammett of Brooklyn, who began her work about the first of January and has made many friends by her diligence in personal effort to bring about the transfer of the Library with the least possible interruption of its availability, her enthusiasm in formulating new methods to adapt it to its new surroundings and increase its usefulness, and the readiness with which she has become acquainted with its frequenters and their necessities. Thus far an assistant, Miss Gladys Byrd, has been employed to expedite the completion of new arrangements.

The thanks of the Committee are due to Charles L. Clarke, one of our members, who has made valuable contributions to the plans for enlargement, radical rearrangement, and protection of the books during the transition period, and has served as secretary of the Committee and otherwise frequently assisted the members of the Committee, particularly in the work of furnishing the business offices of the Institute on the tenth floor, with which special duty the Committee was entrusted by the Board of Directors early in the present Institute year, in preparation for the occupancy which was fully accomplished shortly before the formal dedication.

Of the $4000 appropriated for these furnishings, the Committee expended $1195.81 for carpets, linoleum and other floor coverings, and $2614.41 for furniture of the office, reception, editorial, stenographers', and Board rooms; thus leaving a balance now standing unexpended of $189.78.

Respectfully submitted

The Library Committee
CHAS. F. CHANDLER
CHAS. A. TERRY
EDWARD CALDWELL
FRANK N. WATERMAN
W. J. JENKS, *Chairman.*

CONSTITUTION.

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

[*Incorporated March* 16, 1896.]

[*Adopted May* 13, 1884. *Amended December* 8, 1885, *September* 27, 1892, *May* 15, 1894, *March* 16, 1896, *May* 21, 1901, *and May* 21, 1907.]

ARTICLE I.

1. The name of this association is the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

2. Its objects shall be the advancement of the theory and practice of Electrical Engineering and of the allied Arts and Sciences and the maintenance of a high professional standing among its members. Among the means to this end shall be the holding of meetings for the reading and discussion of professional papers and the publication of such papers, discussions and communications as may seem expedient.

ARTICLE II.

MEMBERSHIP.

3. The membership of the INSTITUTE shall consist of Honorary Members, Members and Associates. Members and Associates shall be equally entitled to all the rights and privileges of the INSTITUTE, excepting that Members only shall be eligible to the offices of President and Vice-President, and shall be entitled to a diploma. Honorary Members shall be entitled to all the rights and privileges of the INSTITUTE, except the right to vote for officers and to hold office.

4. A Member shall be not less than twenty-seven years of age and shall be:

a. A Professional Electrical Engineer; or

b. A Professor of Electrical Engineering; or

c. A person who has done important original work of recognized value to electrical science; or

d. A person duly qualified as an engineer in an allied branch of engineering, and who, for a period of two years, has had responsible charge of electrical engineering work and whose professional record indicates that he is competent to design, as well as direct, electrical engineering works.

5. To be eligible to the grade of Member as a professional Electrical Engineer, the applicant shall have been in the active practice of his profession for at least five years; he shall have had responsible charge of work for at least two years, and shall be qualified to design as well as direct electrical engineering works. Graduation from a School of Engineering of recognized standing shall be considered the equivalent of one year's active practice.

6. To be eligible to the grade of Member as Professor of Electrical Engineering, the applicant shall have been in responsible charge of a course of Electrical Engineering at a college or technical school of recognized standing, for a period of at least two years.

7. An Associate shall be a person not less than twenty-one years of age who is interested in, or connected with, the study or application of electricity.

8. Honorary Members may be chosen from among those who have rendered acknowledged eminent service to electrical engineering or its allied sciences.

ARTICLE III.

Admission, Transfer and Expulsion of Members.

9. Honorary Members shall be proposed in writing by at least ten Members, and may be elected only by the unanimous vote of the Board of Directors, a ballot in writing to be forwarded by members absent from the Directors' meeting. The election of an Honorary Member shall be deemed invalid if an acceptance is not received within six months after the date of his election.

10. All applications for admission to the Institute shall be made for the grade of Associate, in a form prescribed by the Board of Directors, and shall refer to at least three (3) Members or Associates. In applying for admission to the Institute as Associate, any person may also apply at the same time for immediate transfer to the grade of Member Such

application for transfer may also be made at any time subsequent to election as Associate.

11. An application for transfer from the grade of Associate to that of Member shall be made in a form prescribed by the Board of Directors, and shall embody a full record of the general technical education of the candidate and of his professional career. It shall be signed by the applicant and shall refer to at least five Members who know him personally and are familiar with his work. Each of these references shall be requested by the Secretary to fill out a prescribed confidential form, to be addressed to the Board of Directors. No such applications for transfer shall be considered until at least five favorable replies have been received. The Board of Directors, or the Board of Examiners, in the event of failure of replies or receipt of unfavorable replies, may call upon the applicant to furnish additional names. Should an applicant for transfer certify that he is not personally known by five Members, the Board of Examiners may accept, for the deficiency, references to professional engineers of standing.

12. The reference to Members to whom an applicant is personally known may be waived in case of foreign applications; but the applicant shall in that case refer to at least two professional engineers of recognized standing.

13. The Secretary shall issue at stated intervals to each Member and Associate whose address is known, a list of new applications for admission to the INSTITUTE, with the request that the Members and Associates make written communication to the Board of Directors, in case of objection to any of the candidates named. The Board of Directors shall not act upon any name until at least twenty days after the date of issue of said list.

14. All elections as Associates, and transfers to the grade of Membership, shall be by vote of the Board of Directors; two negative votes shall exclude a candidate.

15. The Board of Directors may refuse to elect or transfer any applicant whose character, reputation or professional conduct would make him, in the opinion of the Board of Directors, an undesirable member.

16. A member of any grade in the INSTITUTE may resign his membership by a written communication to the Secretary, who shall present the same to the Board of Directors; whereupon, if all his dues and other indebtedness have been paid, as

provided in the Constitution and By-Laws, his resignation shall be accepted.

17. Upon the written request of ten or more Members or Associates that, for cause stated therein, a Member or Associate of the INSTITUTE be expelled, the Board of Directors shall consider the matter, and if there appears to be sufficient reason, shall advise the accused of the charges against him. He shall then have the right to present a written defence, and to appear in person or by duly authorized representative before a meeting of the Board of Directors, of which meeting he shall receive notice at least twenty days in advance. Not less than two months after such meeting, the Board of Directors shall finally consider the case, and if in the opinion of the Board of Directors a satisfactory defence has not been made, and the accused member has not in the meantime tendered his resignation, he shall be expelled.

ARTICLE IV.

DUES.

18. The entrance fee, payable on admission to the INSTITUTE shall be five (5) dollars. A fee of ten (10) dollars shall be paid on transfer to the grade of Member, which shall include the fee for a diploma.

19. The annual dues shall be fifteen (15) dollars for Members and ten (10) dollars for Associates.

20. Honorary Members shall be exempt from all payments.

21. Persons elected after any portion of the fiscal year shall have expired, shall pay dues pro rata for the unexpired quarters of that fiscal year.

22. A Member or Associate in good standing, by the single payment of two hundred (200) dollars, in addition to his entrance fee, shall become exempt from all future payments for dues or transfer fee. The money thus paid shall be invested as a special fund, to be known as the " Life Membership Fund," from which there shall be taken out and appropriated for the general expenses of the INSTITUTE each year until the death or resignation of said Member or Associate, the sum of ten (10) dollars. Upon the death or resignation of any such Member or Associate, the residue from said payment, including the interest thereon, remaining in the said fund, shall be transferred to the general fund of the INSTITUTE.

23. A Member or Associate who has been dropped as delinquent may be reinstated by the Board of Directors upon payment of all back dues, retaining his original date of election, and shall be entitled to a complete file of the published TRANSACTIONS corresponding with said payment, provided the same are available.

ARTICLE V.

OFFICERS.

24. The officers of the INSTITUTE shall be a President, six Vice-Presidents, twelve Managers, a Secretary, and a Treasurer, who shall hold office as follows:

25. The President, the Secretary, the Treasurer, for one year, the Vice-Presidents for two years, and the Managers for three years. The President, Vice-Presidents and Managers, shall not be eligible for immediate re-election to the same office. A Vice-President shall not be eligible for immediate election to the office of Manager. At each Annual Meeting, the President, three Vice-Presidents, four Managers, the Secretary and the Treasurer shall be elected in the manner prescribed below, and their terms of office shall commence on the first of August next succeeding their election.

26. The terms of the Officers elected at the Annual Meeting at which this constitution is adopted, shall begin on the fourth Friday in September following, instead of on the first of August, as provided in Section 25.

27. A vacancy in the office of President shall be filled by the senior Vice-President; a vacancy in the office of Vice-President shall be filled by the senior Manager. Seniority between officers of same rank and date of election shall be determined by the date of their election as Associates. All other vacancies shall be filled by the Board of Directors for the unexpired term. Such succession to office or appointment by the Board of Directors shall not render an officer ineligible for immediate election to the same office.

28. No officer shall receive, directly or indirectly, any salary, compensation or emolument from the INSTITUTE, either as such officer or in any other capacity, unless authorized by a vote of a majority of the entire Board of Directors.

29. No officer shall be interested, directly or indirectly, in any contract relating to the operations conducted by the

INSTITUTE, nor in any contract for furnishing supplies thereto, unless expressly authorized by the By-laws or by the unanimous vote of the members of the Board of Directors present at any meeting.

ARTICLE VI.

ELECTION OF OFFICERS.

30. During the first week in February of each year, the Secretary shall mail or deliver to each Member and Associate of the INSTITUTE, a list of all Members and Associates, together with a form showing the offices to be filled at the ensuing annual election in May, and containing the names of the incumbents and a copy of sections 30 and 31 of this Article, with the request that nominations be made for the various offices to be filled. These nominations shall not be signed, and shall be enclosed in an envelope, identified on the face by the name of the sender and mailed to the Secretary. To be considered, nominations must reach the Secretary prior to March first. The nomination ballots shall be counted and canvassed by the Committee of Tellers appointed as provided in Sections 34 and 35.

31. The Committee of Tellers shall submit to each member of the Board of Directors prior to the March meeting, a classified list of all nominations received, from which the Board of Directors shall prepare, during the month of March, a complete ticket, to be headed: Directors' Nominees," containing the names of those whom the Board of Directors deem best suited for the offices falling vacant; provided that upon the request of two Directors at the meeting at which the " Directors' Nominees " ticket is prepared, the name of a second nominee for President shall be placed on the ticket, selected from the four names receiving the highest number of nomination votes for President, and provided further, that upon the request of two Directors at the same meeting, the names of one or more additional nominees for Vice-President, and upon like request, the names of one or more additional nominees for Manager shall be placed upon the ticket. The names on the Directors' Nominees ticket shall be listed in the order of the number of nomination votes received, beginning with the highest number. This ticket shall be printed on the same sheet with a second list, headed ' General Proposal List," containing all the eligible names pro-

posed, and the number of votes cast for each; provided that no name shall appear which shall not have received at least three per cent. of the entire number of votes cast.

32. The voting for officers shall be restricted to the names of the "Directors' Nominees" and the names on the General Proposal List provided for in section 31 of this Article. This List, together with an envelope on which shall be printed the title of the INSTITUTE, the name and address of the Secretary and the words "Official Voting Envelope—Enclosing a Ballot Only," shall be mailed by the Secretary not later than the first day of April, to every Member and Associate, together with a copy of sections 32 and 33 of this Article; provided that any qualified Member or Associate not having a ballot and envelopes shall be entitled to obtain them from the Secretary at any time before the first day of May.

33. All names voted for shall be written, printed or otherwise marked on a single ticket or ballot, which shall be enclosed in a sealed, unmarked and unidentified inner envelope of any suitable character, which shall in turn be enclosed either in the "Official Voting Envelope" (received from the Secretary), or any other envelope, marked on its face, "Non-Official Voting Envelope—Enclosing a Ballot Only." The outer envelope of either class shall be identified by the name of the sender on its face, shall be sealed, and in order to be counted, shall reach the Secretary not later than the first day of May. The Secretary shall preserve, unopened, for ninety days, all ballots received after the first day of May.

34. The President, at the Directors' meeting to be held in February, shall appoint, subject to the approval of the Board of Directors, five Members or Associates, not members of the Board of Directors, to constitute the Committee of Tellers; should this Directors' meeting not be held, the President, previous to the twenty-first of February, shall appoint this Committee by letter to the Secretary, who shall notify the members thereof.

35. Any Member or Associate who shall deliver to the Secretary on or before the first day of March, a written petition signed by at least twenty Members or Associates, stating their desire that he be a member of the Committee of Tellers, shall also be a member of that Committee; provided that the aforesaid signatures shall not have appeared on another similar petition.

36. The Committee of Tellers shall meet at the office of the INSTITUTE as soon after the first day of May as possible, and shall receive, unopened, all ballots from the Secretary, who shall also make to it a written report of the number of ballots received on and before, and after, the first day of May. It shall forthwith proceed, in secret, to count the vote, and shall prepare and sign in duplicate a report of the results of the vote, which shall be sealed, and of which one copy shall forthwith be filed with the Secretary, and of which the other copy shall remain in possession of the Chairman of the Committee who shall hand this report to the presiding officer at the ensuing Annual Meeting. In the absence of this report by the Chairman of the Committee, the Secretary shall produce the duplicate copy, and hand the same to the presiding officer of the meeting. The presiding officer shall cause the report to be read, at the first session of the Annual Meeting and shall declare duly elected the eligible persons receiving the greatest number of votes for the respective offices.

ARTICLE VII.

MANAGEMENT. DUTIES OF OFFICERS AND COMMITTEES.

37. The affairs of the INSTITUTE shall be managed by a Board of Directors under this Constitution and the general provisions of the laws under which it is incorporated. The Board of Directors shall consist of the President, two Junior Past-Presidents, the Vice-Presidents, the Managers, the Secretary and the Treasurer.

38. The Board of Directors shall have such powers and duties as are prescribed by statute for a Board of Directors.

39. The Board of Directors shall direct the investment and care of the funds of the INSTITUTE, shall make appropriations for specific purposes, shall pass upon all applications for admission or for transfer, shall act upon all questions of expulsion of members, shall appoint all employees and fix their salaries, and in general shall direct the business of the INSTITUTE, either itself or through its officers and committees.

40. The Board of Directors shall prepare and adopt a series of By-laws which shall govern its procedure and that of the Committees, under this Constitution. Such By-laws shall be adopted or may be amended by a concurring vote of not less than twelve (12) members of the Board of Directors; provided,

that the text of a proposed By-law or amendment shall be furnished to each member of the Board of Directors at least ten days before the meeting at which a vote on the same will be taken.

41. The President shall have general supervision of the affairs of the INSTITUTE, under the direction of the Board of Directors. He shall preside at the meetings of the INSTITUTE, and of the Board of Directors at which he may be present, and shall be *ex-officio* member of all committees. He shall deliver an address at the Annual Convention. The Vice-Presidents, or in their absence, the Managers, in order of seniority, shall preside at meetings of the INSTITUTE and the Board of Directors in the absence of the President, and shall discharge his duties in case of a vacancy in the office. The President shall appoint the standing committees of the INSTITUTE. He may also appoint special committees from time to time.

42. The Secretary shall be the executive officer of the INSTITUTE under the direction of the President and the Board of Directors, He shall attend all meetings of the INSTITUTE and of the Board of Directors, and record the proceedings thereof. He shall collect and deposit, subject to the order of the Treasurer, all moneys due the INSTITUTE, reporting such deposit to the Treasurer, who shall receipt for the same. He shall personally certify the accuracy of bills or vouchers on which money is to be paid, and shall draw and countersign all checks, and these shall be signed by the Treasurer when such drafts are known to him to be proper, and duly authorized by the Finance Committee and in accordance with warrants executed by the Secretary. He shall have charge of the books and accounts of the INSTITUTE. He shall present annually to the Board of Directors a balance sheet, and from time to time shall furnish such statements as may be required. He shall conduct the correspondence of the INSTITUTE, and shall keep full records. He shall be in responsible charge, under the President and the Board of Directors, of all the property of the INSTITUTE. He shall, with the approval of the Board of Directors, employ such clerical force as may be necessary and shall be responsible for the work of all employees of the INSTITUTE. He shall perform such other duties as may be assigned to him. His entire time must be devoted to the affairs of the INSTITUTE, unless otherwise authorized by the Board of Directors. He

shall be paid a salary to be fixed by the vote of a majority of the entire Board of Directors.

43. The Treasurer and the Secretary shall invest such funds as may be ordered by the Board of Directors. They shall also pay bills when audited by the Finance Committee and approved by the Board of Directors. The Treasurer shall make an annual report and such other reports as may be prescribed

44. The Board of Directors may delegate any or all of its powers to an Executive Committee of seven members, consisting of the President, the Secretary, and the Treasurer, *ex-officio*, and four other members of the Board of Directors, which committee shall conduct the affairs of the Board of Directors between its meetings.

45. The Board of Directors or the Executive Committee (subject to the direction of the Board) may at any time authorize any officer, director, or other person to perform any acts or functions, which in the Constitution or By-laws may be prescribed to be performed by any specified officer or other person, whenever by reason of death, absence, disability or other cause, sufficient ground therefor shall appear to the Board or Executive Committee.

46. The Standing Committees to be appointed by the President as specified in section 41 shall be the following:

A Finance Committee of three members.
A Library Committee of five members.
A Meetings and Papers Committee of five members.
An Editing Committee of three members.
A Board of Examiners of five members.
A Sections Committee of five members.
A Standards Committee of nine members.
A Code Committee of seven members.
A Law Committee of five members.

The Board of Directors may appoint auxiliary members to any committee. The members of the Finance Committee shall all be members of the Board of Directors. All other standing committees shall include at least one member of the Board of Directors. All members of the Board of Examiners shall be Members of the INSTITUTE. All committees shall be directly responsible to the Board of Directors, and shall act under its directions. The Board of Directors may, at any time, at its own discretion, remove any or all members of any committee and appoint others. The terms of the members of all standing and special committees shall terminate at the close of the first meeting of the Board of Directors following the Annual Meeting.

47. All official communications of committees to the Board of Directors shall be made through the Secretary unless otherwise specially ordered by the Board of Directors.

48. In addition to the duties and powers hereinafter ascribed to committees, these committees shall perform such other duties, and shall have such other powers, as may be specified in the By-laws, or as may be delegated to them by the Board of Directors.

49. The Finance Committee shall have direct supervision of the financial affairs of the INSTITUTE. It may employ an expert accountant to assist in auditing the accounts. It shall approve all bills before payment, and shall make recommendations to the Board of Directors regarding the investment of moneys, and all specific appropriations. No payments other than for routine office expenses shall be made by the Secretary or Treasurer except upon the authorization of the Finance Committee.

50. The Library Committee shall have general supervision of the Library of the INSTITUTE. The committee shall make recommendations to the Board of Directors with reference to the Library, and shall direct expenditures for books or other articles for the same, of such sums as may be appropriated for these purposes.

51. The Meetings and Papers Committee shall arrange for the meetings of the INSTITUTE, and for the preparation and discussion of the papers to be presented before the INSTITUTE. The committee shall decide all questions regarding the acceptance or rejection of any paper submitted for presentation before the INSTITUTE, and all questions regarding the publication of papers presented before the INSTITUTE or any of its Sections.

52. The Editing Committee shall edit all discussions of the papers presented at any meeting of the INSTITUTE, and all communications in reference thereto, and shall decide all questions regarding the publication of discussions and communications in the PROCEEDINGS and TRANSACTIONS of the INSTITUTE or otherwise.

53. The Board of Examiners shall pass upon the qualifica-

tions of all applicants for election or for transfer, whose applications have been received by the Secretary, and which are in conformity with Sections 10, 11, and 12 of Article 3, and it shall report its findings to the Board of Directors for action.

54. The Sections Committee shall have the general supervision and management of the Sections and Branches of the INSTITUTE. The committee shall confer with the Sections and Branch officers, and it shall consider, investigate, and make reports and recommendations to the Board of Directors for action upon all matters regarding or involving the interests and the welfare of Sections and Branches, or the relations between these organizations and the INSTITUTE.

55. The Standards Committee shall consider and investigate all matters relating to units and standards appertaining to or applicable in electrical engineering and in the allied arts and sciences. The Committee shall make reports and recommendations to the Board of Directors for action thereon.

56. The Code Committee shall consider and investigate all matters relating to the formulation of rules for the protection of persons and property against fire and other hazards in connection with electrical installations and equipments, and shall confer with similar committees of other bodies regarding the same. The Committee shall make reports and recommendations to the Board of Directors for action thereon.

57. The Law Committee shall consider and investigate all matters relating to the Constitution and By-laws of the INSTITUTE, the duties and jurisdiction of its officers and committees, its legal status and responsibilities and like legal and cognate questions; also all other matters referred to it by the Board of Directors, the President or the Secretary. The Committee shall make reports and recommendations to the Board of Directors for action thereon. The Committee may consult legal and technical counsel with reference to any question before it.

58. The Board of Directors may, at its discretion, appoint Local Honorary Secretaries to represent the INSTITUTE in foreign countries. Such appointments shall be made for a period of two (2) years and may be renewed.

59. The following numbers shall constitute a quorum of the Board of Directors:

For all business prescribed by statute for a Board of Directors

—twelve members or such larger number as the statute may require.

For expulsion of Members—fifteen members.

For all other business—five members.

60. Unless otherwise specifically provided in this Constitution, the action of the Board of Directors shall, in all cases, be determined by the concurring vote of a majority of the members present, providing there exists the quorum required for the particular business.

ARTICLE VIII.

MEETINGS.

61. The Annual Meeting of the INSTITUTE shall be held in the city of New York, beginning on the second Friday in May, when a report of the proceedings of the INSTITUTE for the past fiscal year shall be furnished by the Board of Directors. This report shall be verified by the President, Treasurer and Secretary and approved by the Board of Directors. It shall show: the whole amount of real and personal property owned, where located, where and how invested; the amount and nature of the property acquired during the past fiscal year and the manner of its acquisition; the amount applied, appropriated or expended during the year, and the purposes, objects or persons to or for which such applications, appropriations or expenditures have been made; the names and places of residence of persons who have been admitted to membership in the INSTITUTE during such year; and all other facts bearing upon the status of the INSTITUTE. This report shall be filed with the records of the INSTITUTE and an abstract thereof entered in the minutes of the Annual Meeting. The reports of all officers and of the standing committees shall be presented at the Annual Meeting, and the vote for officers for the ensuing year shall then be announced. In addition to the above, professional papers and the discussions thereof arranged for by the Meetings and Papers Committee may be presented, and any other business may be brought before and transacted, at this meeting.

62. There shall be held outside of the city of New York not later than August first an Annual Convention of the INSTITUTE, for the presentation and discussion of professional papers, and for the transaction of other business not affecting the organization or policy of the INSTITUTE. All questions affecting the

organization or policy of the INSTITUTE may be brought up for discussion at this Convention, and may be referred by a majority vote to the Board of Directors, with recommendations. The time and place of such Convention shall be fixed by the Board of Directors.

63. Special meetings of the INSTITUTE for the transaction of business may be called by the Board of Directors at any time, by written notice stating the specific object thereof mailed to each Member and Associate at least thirty (30) days prior to the date of said meeting.

64. Other meetings of the INSTITUTE may be held at such times and places as the Board of Directors shall select, at which no business affecting the organization or policy of the INSTITUTE shall be transacted. Notice of all meetings specified in this Article of the Constitution shall be sent by mail, or otherwise, to all Members and Associates, at least ten days in advance.

ARTICLE IX.

INSTITUTE SECTIONS AND BRANCHES.

65. Whenever, in the judgment of the Board of Directors, a sufficient number of Members and Associates shall petition, in writing, these members may form, subject to the Constitution and all By-laws and regulations which may be hereafter prescribed by the Board of Directors a Section organization for the purpose of more effectually carrying out the aims of the INSTITUTE.

66. Any Member or Associate may become a member of such Section, but a Member or Associate shall be entitled to vote, or hold office, in one Section only.

67. The officers of each Section shall consist of a Chairman, a Secretary, and such other officers as each Section may find desirable. These officers shall be elected by the votes of the Members and Associates of that Section, in the manner provided in the Section By-laws. The election of any Member or Associate as a Section officer, shall not debar him from election or appointment to any other office in the INSTITUTE.

68. The Chairman of the Section shall perform the duties usually devolving upon the Chairman of any organization, and in addition shall be *ex-officio* a member of the Sections Committee of the INSTITUTE. He shall have the privilege

of appearing before the Board of Directors at any meeting, on giving due notice of his intention to do so, for the purpose of conference with the Board of Directors, in regard to any matters pertaining to the affairs of the INSTITUTE in his Section. The Chairman shall perform such other duties and shall have such other powers as may be delegated to him by the Board of Directors.

69. The Secretary shall report the Proceedings of the Section to the Secretary of the INSTITUTE; he shall, in general, discharge the duties of a Secretary both to the Section itself and in its relation to the INSTITUTE; he shall perform such other duties as may be prescribed in the Section By-laws, or in the By-laws of the INSTITUTE, or delegated to him by the Board of Directors.

70. Each Section may have the privilege of being represented at the Annual Convention, by an official delegate, who shall be the Chairman of that Section, or, in his absence or inability to attend, by an alternate delegate selected by the Section. The official delegate attending the Annual Convention may have his expenditures for transportation refunded by the INSTITUTE, as provided in the By-laws.

71. The Sections may hold meetings at such times and places as may be determined by their officers, for the purpose of carrying on their work.

72. Any Section may adopt for its own government such By-laws to be known as "Section By-laws" as it may find expedient, provided that no provision thereof shall be incompatible with the Constitution or the By-laws of the INSTITUTE.

73. University Branches may be formed and Student meetings may be held as provided in the By-laws.

74. Sections and Branches may be dissolved in the manner specified in the By-laws for failure to comply with the Constitution and By-laws of the INSTITUTE.

ARTICLE X.

GENERAL.

75. A quorum of the INSTITUTE at the Annual Meeting shall consist of not less than five per cent. of the total number of Members and Associates, present in person or by proxy. The same number shall constitute a quorum for the transaction of

business at the Annual Convention and at special meetings called as provided in section 63.

76. Every Member or Associate entitled to vote at any meeting may so vote by proxy, signed by the Member or Associate, and filed with the Secretary before the meeting at which it is to be voted. No proxy shall be valid after the expiration of eleven (11) months from the date of its execution, unless the Member or Associate executing it shall have specified therein the length of time it is to continue in force, which shall be for some limited period. Every proxy shall be revocable at the pleasure of the person executing it.

77. The Committee of Tellers named in Article VI., sections 34–35, shall be considered a proxy committee for the definite purpose of formally voting, at the annual election, letter ballots named in Article VI., sections 32–33, and canvassed by them as stated in section 36.

78. The fiscal year of the INSTITUTE shall terminate with the thirtieth day of April.

ARTICLE XI.

AMENDMENTS.

79. Amendments to this Constitution may be proposed by means of a petition signed by not less than one hundred (100) Members or Associates and received by the Secretary not later than February first; or by means of a Resolution adopted by the Board of Directors not later than February first. Such proposed amendment or amendments shall be submitted to legal counsel by the Board of Directors, and if, in the opinion of such counsel, they are in accordance with the laws under which the INSTITUTE is organized, a copy shall be mailed, with a letter ballot, to each Member and to each Associate, not less than sixty (60) days before the Annual Meeting.

80. Votes, to be considered, shall be received by the Secretary not later than one week before the Annual Meeting. The Secretary shall hand these votes unopened to the Committee of Tellers, which shall count such votes and make a sealed report to the Board of Directors in duplicate, of which one copy shall forthwith be filed with the Secretary, and of which the other copy shall remain in possession of the Chairman of the Committee, who shall hand this report to the presiding officer at the annual meeting. In the absence of this report by the

Chairman of the Committee the Secretary shall produce the duplicate copy and hand the same to the presiding officer of the meeting. The presiding officer shall then cause the report to be read. If the total vote be not less than thirty per cent. (30%) of the total membership of the INSTITUTE, and if seventy-five per cent. (75%) or more of all the Members and Associates voting shall declare themselves in favor of the proposed amendment or amendments, the same shall become a part of the Constitution.

81. Amendments shall take effect thirty (30) days after their adoption, but officers of the INSTITUTE at the time any amendment becomes effective shall continue in office until the end of the terms for which they were elected.

82. The Secretary shall print copies of the amendments as soon as practicable after adoption, and distribute the same to Members and Associates.

DISCUSSION ON "CONSTANTS OF CABLES AND MAGNETIC CONDUCTORS", AT SCHENECTADY, APRIL 25, 1907 (see p. 555)

W. A. Del Mar (by letter): Mr. Berg may well be surprised to find the great number of different formulas devised to express the inductance of a pair of parallel wires. The variety of formulas is remarkable, considering that a simple and accurate formula has been available in most of the standard mathematical treatises on electricity from Clerk Maxwell to Alex. Russel.

The inductance of a circuit is a measure of the magnetic energy associated with the current in it and is defined by the following well-known equation:

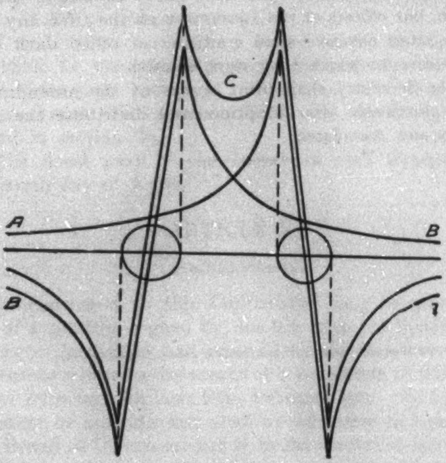

FIG. 1

$$E = \tfrac{1}{2} L i^2$$

where E = energy in magnetic field interlinked with a circuit of inductance L carrying an unvarying current i. In the case of a circuit composed of two parallel wires, the size of which is negligible in comparison with their distance apart, the inductance is approximately equal to the total flux embraced by the circuit due to unit current therein.

In the paper under discussion this approximation is used as the basis of a formula which is apparently intended to be exact.

By a curious the coincidence, the exact formula is of the form given by Mr. Berg as an approximation; that is, it contains a term $\log \frac{2D}{d}$ instead of $\log \frac{D-r}{r}$ as given in the formula referred to above. Even using the approximation as a basis, the deductions given are not correct, owing to an error in the selection of the limits of integration.

When two conductors carrying currents in opposite directions are brought into proximity, the magnetic whirls around the conductors are squeezed together and the axes of the two whirls are pushed away from the axes of the conductors. In order to include the entire flux, the integration should, therefore, have been extended to the axes of the whirls, instead of merely between the axes of the two wires.

This is shown graphically in Fig. 1 in which the ordinates of the curves *A A* and *B B* represent the flux density around a pair of parallel wires, and the ordinates of the curve *C* show the resultant flux density due to the fields of the two wires. It will be noted that the curve of resultant flux density crosses the horizontal axis outside the axes of the wires, and the inductance will be the entire area between the resultant curve and the horizontal axis. The area of this curve expressed as a formula is cumbersome in the extreme and withal useless, because as stated above it is based on incorrect premises.

The equation defining inductance is stated above in terms of an unvarying current because the flux due to a varying current is not distributed in a condition of equilibrium, and is therefore not a definite quantity but depends upon the rate of the variation of the current. The flux due to unit current varying at any particular rate may be called the "effective inductance" at that rate.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers. Niagara Falls, N. Y., June 25, 1907.

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THE PROPERTIES OF ELECTRONS

President's Address

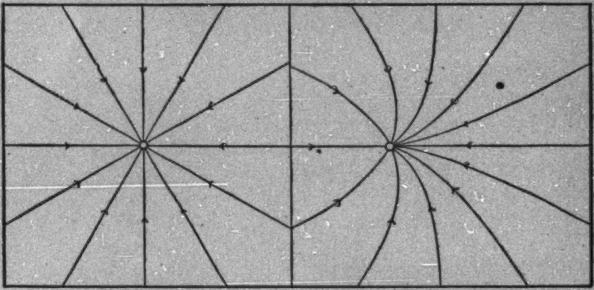
BY SAMUEL SHELDON

Introductory. The physical properties of electrons form the basis of electrical engineering, and a thorough understanding of them is essential for successful investigation in some departments of research. No specific treatment of the subject has appeared in the printed publications of the Institute. It is therefore hoped that what follows will be of service to the membership. No attempt has been made to treat of the conduction of electricity through gases, of the phenomena of radioactivity, or of electrolytic conduction, in all of which the electron plays an important part.

The Electron. Electrons, which are called corpuscles by some physicists, are the smallest particles of matter that have been isolated. They are considered by some (Larmor) to be constituted of ether. Their shape is unknown, but it is frequently assumed as spherical. At ordinary velocities the mass of an electron is 6.3×10^{-28} grams; at rest, its mass may be zero; and at velocities approaching closely to that of light it becomes nearly infinite. Each electron carries an invariable negative electric charge of $1.1\ 10^{-19}$ $[=e]$ coulombs, $= 1.1\ 10^{-20}$ $[=e_m]$ electromagnetic units, $= 3.4\ 10^{-10}$ $[=e_s]$ electrostatic units. Some writers use the term to designate particles carrying positive charges and having other properties. Such use is not common nor desirable.

Electrons in a free condition are present in metallic conductors, in gases, especially at low pressures, and to a limited degree in ordinary solid dielectrics. They are not present in free ether or space. Combined with other electrons and with an unknown something or condition, that gives under certain conditions evidences of positive electrification, electrons are present in all matter. Their properties are in nowise dependent upon the properties of the matter with which they are associated, and they are considered to be indestructible by any agent within the command of man. Every electron is in some manner entangled with the luminiferous ether.

The ether is a fluid plenum or continuum, endowed with the properties of inertia and rotational elasticity, and is the medium through which all forces are exerted. It fills all space between electrons and the bounds of the universe; it is supposed by some to penetrate the electrons, and (Lorentz) remains stagnant during the passage of electrons through it.



Stationary. Moving to the left.

FIG. 1.—Distribution of electric flux from an electron.

Each electron, when isolated and at rest, produces at every point in the ether an elementary electrostatic field, corresponding in direction and intensity to its charge. All electrostatic fields are due to the resultant superpositions of such elementary fields. The force exerted upon an electron in a field of intensity E, produced by a plurality of electrons, is Ee_s dynes, both quantities being expressed in electrostatic units. An electron moving with uniform velocity in a straight line at a velocity v cm/sec produces at every point both an electric field and a magnetic field, and carries them with it. If the motion be in the direction of the Z axis of coördinates, and the velocity be small as compared with that of the propagation of ether disturbances, at a point whose coördinates are x, y, z, the electric field will be radially directed, and have a magnitude E, in electrostatic units, the same as when at rest. With the electron at the origin and with a medium of unit permeability, the equation for E is

$$E = \frac{e_s}{4\pi} \; \frac{1}{(x^2+y^2+z^2)}; \tag{1}$$

and the intensity components α, β, γ, of the magnetic field parallel to the X, Y, and Z axes, respectively, are given by the equations;[1]

$$\left.\begin{aligned} \alpha &= e_m \, v \, \frac{y}{(x^2+y^2+z^2)^{\frac{3}{2}}} \\ \beta &= -\, e_m \, v \, \frac{x}{(x^2+y^2+z^2)^{\frac{3}{2}}} \\ \gamma &= 0 \end{aligned}\right\} \tag{2}$$

For large velocities, the velocity of light being c cm/sec,

$$E = \frac{e_s}{4\pi} \, \frac{c}{(c - v^2)^{\frac{1}{2}}} \left\{ \frac{x^2+y^2+z^2}{\left(x^2+y^2+\dfrac{c^2}{c^2-v^2} z^2\right)^3} \right\}^{\frac{1}{2}}$$

$$\alpha = \frac{e_m \, c \, v}{(c^2 - v^2)^{\frac{1}{2}}} \, \frac{y}{\left(x^2+y^2+\dfrac{c^2}{c^2-v^2} z^2\right)^{\frac{3}{2}}} \tag{3}$$

$$\beta = \frac{e_m \, c \, v}{(c^2 - v^2)^{\frac{1}{2}}} \, \frac{x}{\left(x^2+y^2+\dfrac{c^2}{c^2-v^2} z^2\right)^{\frac{3}{2}}}$$

$$\gamma = 0$$

An electron, with its charge e_m, moving with uniform velocity v cm/sec at an angle θ to the direction of a magnetic field of intensity H, is acted upon by the field with a force whose magnitude is

$$F = H \, e_m \, v \sin\theta \text{ dynes.} \tag{4}$$

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[1] Heaviside, Phil. Mag., p. 324, April, 1889; J. J. Thomson, Cond. of Elect. Through Gases, p. 531.

If an electron, moving with a velocity small compared with c cm./sec. that of light, suffer a change, either in the magnitude of its velocity or in its direction, a radiation of energy between it and the surrounding ether will take place whose magnitude is[2]

$$J = \frac{2}{3} \frac{e_m^2 \ a^2}{c} \text{ erg/sec} \tag{5}$$

where a is the acceleration in cm/sec^2

Charge of the Electron. J. J. Thomson[3] and others have determined the magnitude of the charge carried by a negative gaseous ion, which is the same as that carried by an electron. The method employed for measuring the charge depends upon the discovery[4] that if a dust-free ionized gas, saturated with water vapor, be adiabatically expanded so that the ultimate volume bears to the initial volume a ratio of 1.25, droplets of water will form about the negative ions, but condensation will not occur around the positive ions until this ratio reaches the value 1.31. when droplets will form about both ions. Using an expansion of ratio 1.25, the charge on a negative ion can be found from a determination of the number of droplets and of the total charge on all the droplets. The number of droplets is obtained from a determination of the size of each droplet and the weight of all of them. The total weight can be obtained from the known properties of gases that are saturated with water vapor. The size of the droplets can be obtained from the rate at which the cloud, that they form in the enclosing receiver, settles. According to Stokes' law, the terminal velocity u cm/sec of a sphere of radius r cm and excess of density d, falling through a gas of which the coefficient of viscosity is η, is expressed by the equation

$$u = \frac{2}{9} \ \frac{d g r^2}{\eta},$$

whence

$$r = \sqrt{\frac{9 \eta u}{2 g d}}, \tag{6}$$

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[2] Larmor, Æther and Matter, p. 227; Phil. Mag., Dec., 1897, p. 512.

[3] J. J. Thomson, Phil. Mag., Dec., 1898, Dec., 1899.

[4] C. T. R. Wilson, Phil. Trans., A., 1897, p. 265.

g cm/sec² being the acceleration due to gravity. From observation of u and a determination of η the value of r is obtained.

The droplets upon falling are allowed to collect in an insulated receptacle connected with an electrometer. H. A. Wilson[5] checked the determination of the size of the droplets by observing their rate of movement in a strong electric field arranged to act against or with gravity.

The total charge was determined by Thomson by impressing a small potential difference v volts upon two parallel horizontal electrodes so placed as to include between them all the ionized gas, and by measuring the current-density I ampere/cm² which flowed through the gas. Let N = total number of ions per cubic cm, positive as well as negative, e = charge on each ion in coulombs, u' = sum of velocities under a gradient of one volt/cm, of positive and negative ions (determined by a special method), and l the distance between the electrodes, then the charge on each ion is

$$e = \frac{l\,i}{N\,u'\,V} \text{ coulombs.} \tag{7}$$

Thomson's latest value for e_s is $3.4\ 10^{-10}$, using an expansion ratio of 1.31 and thereby obtaining the total number of positive and negative ions.

Mass of the Electron. Many determinations of the ratio of the charge on an electron to its mass m have been made, from which, knowing the charge, the mass can be obtained. One method, used by Thomson, was to pass a stream of electrons, projected from a cathode in a highly exhausted tube, through a magnetic field of uniform intensity H and perpendicular in direction to the path of the electrons. If the electrons be moving with a velocity v cm/sec, the field will exert a force $e_m\,v\,H$ dynes upon them, and they will move in a circular path whose radius can be determined from the observed deflection of the stream; and has a value, as in any case of centripetal acceleration, of

$$r = \frac{m\,v}{e_m\,H} \text{ cm}$$

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[5] H. A. Wilson, Phil. Mag., April, 1903.

whence
$$m = \frac{r\,e_m\,H}{v} \text{ grams.} \tag{8}$$

To obtain v the electrons must simultaneously be subjected to the influence of an electric field of intensity E in electrostatic units, whose direction is perpendicular to the lines of force of the magnetic field and also to the original path of the electrons. By adjusting the intensity and sign of the electric field until the force it exerts upon each electron, $E\,e_s$, is equal and opposite to that exerted by the magnetic field, it follows that

$$E\,e_s = H\,e_m\,v, \tag{9}$$

or
$$v = \frac{E\,e_s}{H\,e_m},$$

and
$$m = \frac{r\,e_m\,H^2}{E}\;\frac{e_m}{e_s} \text{ grams.} \tag{10}$$

Another method of obtaining an expression for v, involving m and measurable quantities, used by Thomson, was to allow the electrons to bombard the face of a thermopile whose rate of increase of temperature could be determined from the rate of increase of the thermoelectromotive force. If the face of the thermopile be bombarded by N electrons per second, moving with a velocity v cm/sec, heat will be communicated to it at such a rate dk/dt that

$$\mathbf{K} = dk/dt = \tfrac{1}{2}\,N\,m\,v^2. \tag{11}$$

If the charges of the electrons be allowed to pass to an insulated conducting system connected with an electrometer, the rate of increase of negative charge can be obtained, and is

$$\mathbf{e} = de/dt = N\,e.$$

Therefore
$$v = \sqrt{\frac{2\,e\,\mathbf{K}}{m\,\mathbf{e}}}, \tag{12}$$

and
$$m = \frac{r^2\,e\,H^2\,\mathbf{e}}{2\,\mathbf{K}}. \tag{13}$$

Another method of obtaining an expression for v, used by Kaufmann[6] and by Simon,[7] is based upon the assumption that all the kinetic energy of the electrons is represented by the energy that would be required to transfer their charges between two points having a difference of potential V equal to that existing between the cathode and the anode of the containing tube.

In this case
$$\tfrac{1}{2} N m v^2 = V N e, \tag{14}$$

and substituting the value of v in (8),

$$m = \frac{r^2 e H^2}{2 V}. \tag{15}$$

This method gives too large values because it does not take account of the energy lost in collisions, and that required to detach the electron from the cathode.

Many other methods of determining m have been employed; all yielding values of the same order of magnitude, but differing considerably from one another. The first determination of the ratio e_m/m was made by Zeeman in connection with his experiments on the influence of the magnetic field upon the spectra of gases. The values obtained by various methods, and upon electrons obtained in various ways are given in the following table[8] from Lorentz:

Method.	$\frac{e_m}{m} 10^{-7}$	v/c
Zeeman effect	1.6 to 3	0.1 to 0.3
Rotation of plane of polarized light	0.9 to 1.8	
Cathode rays (Simon)	1.86	
Cathode rays (other observers)	0.7 to 1.4	
Ultra violet rays on zinc	0.7	
Radium β rays	1.75	Small.

The differences between the values obtained are probably due to some of the electrons being loaded with matter, and to the various velocities with which they were moving.

The influence of velocity upon mass has been determined by Kaufmann in the case of electrons ejected from radium preparations in the form of β rays.

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[6] Kaufmann, Wied. Ann., 61, p. 544; 62, p. 596; 65, p. 431.

[7] Simon, Wied. Ann., 69, p. 589.

[8] Lorentz, Electrotechnische Zeits., June 15, 1905, p. 558.

Suppose a charged electron to be moving in a curved path, and to be accelerating both tangentially and radially. Let the tangential acceleration be a_1 and the radial be a_2. Inasmuch as a moving electron produces a magnetic field, whose lines are circular and lie in a plane perpendicular to the direction of motion and whose intensity at any point is proportional to the velocity of the electron, the acceleration must be accompanied by an increasing strength of field. As this increase requires that work be performed upon the ether, part of the force which causes the acceleration must be used in performing this work.

Let m_1 and m_2 represent two coefficients, which, when multiplied, respectively, by the accelerations a_1 and a_2, give the forces required to perform this work represented by the increasing intensity of the two components of the magnetic field. Then, if m_0 be the mass as ordinarily understood, of the electron, the tangential and radial components of the force, respectively, will be

$$\left.\begin{aligned} f_t &= a_1\,(m_0+m_1) \\ f_r &= a_2\,(m_0+m_2) \end{aligned}\right\}\text{dynes} \qquad (16)$$

The coefficients m_1 and m_2 appear, therefore, to represent, respectively, longitudinal and transverse electromagnetic masses of the electrons, which it is assumed have also a true mass m_0.

Now m_1 and m_2 are not constant, but depend upon the velocity of the electron, as shown in equations (2), (3) and (5). For small velocities, as compared with that of light, if the electron be assumed as spherical of radius R cm. and with its charge e_m spread uniformly over its surface, m_1 and m_2 each have the value;[9]

$$m_1 = m_2 = \tfrac{2}{3}\;\frac{e^2_m}{R} \qquad (17)$$

For greater velocities these values increase, until at the velocity of light they become infinite. Using analytical results obtained by Abraham, Kaufmann concludes from his experiments upon the deflection of β rays that, within the limits of experimental errors, (m_0+m_2) varies with the velocity as m_2 should, and therefore $m_0 = 0$, that is, a stationary electron has no mass whatsoever, and all the mass of a moving electron is due to its entanglement with the ether. The values determined by Kaufmann and the percentage difference from theoretical values based upon the assumption $m_0 = 0$ are given in the following table:[10]

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[9] Thomson, Recent Researches in El. and Mag. 1893, p. 21.

v/c	m_2/m Observed	Per cent. variation from theoretical
Small	1.	——
0.732	1.34	−1.5
0.752	1.37	−0.9
0.777	1.42	−0.6
0.801	1.47	+0.5
0.830	1.545	+0.5
0.860	1.65	0.
0.883	1.73	+2.8
0.933	2.05	−7.8 (?)
0.949	2.145	−1.2
0.963	2.42	+0.4

The following curve shows the relation which exists between the mass of an electron, expressed in terms of its mass at low speeds, and its velocity expressed in terms of that of light.

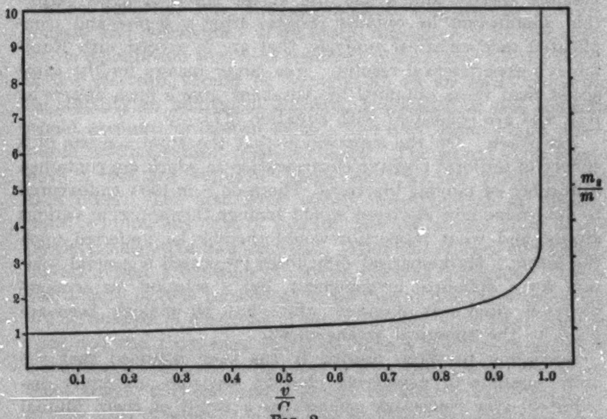

FIG. 2.

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[10] Rutherford, Radio-Activity, p. 111.

The mass at small velocities is 6.3 10^{-28} grams. At a velocity equal to that of light, the magnetic flux surrounding an electron in a plane perpendicular to its path and passing through it, should become infinite; this follows from the substitution of $v=c$ and $z=0$ in equations (3). The electron thereby would acquire an infinite self-inductance. Consequently, an infinite force would need to be exerted upon it in order to produce a finite acceleration. The mass of the electron, therefore, at this hypothetical velocity would be infinitely large.

Size of the Electron. If it be assumed that the electron is spherical in shape, then, knowing its charge e_m and its apparent mass at low speeds m_1, its radius R can be obtained from equation (17)

$$R = \frac{2}{3} \; \frac{e^2{}_m}{m_1} = 1.3 \; 10^{-} \text{ cm} \tag{18}$$

which is much smaller than the diameter of atoms. Lorentz has been led to conclude, from the consideration of various phenomena appearing in moving systems of different kinds, that the electron is spherical when at rest, ellipsoidal at intermediate speeds, and a flat disc at the speed of light. Upon this assumption he obtains results, after a severe and complicated mathematical analysis, that are in accord with Kaufmann's experimental results, give larger masses for the same speed than those obtained by Abraham, give a mass of zero at rest, and are consistent with equation (17).

The Atom. On the supposition that the atom consists of a sphere of uniform positive electrification in which are contained a number of moving electrons. Thomson,[11] in 1904, endeavored to determine how electrons would arrange themselves in various atoms, and what properties would thereby be conferred upon the latter. Mathematical difficulties prevented a general solution for a spherical arrangement, but a solution for arrangements in rings was obtained. which has, by analogy, been applied to the spherical arrangement.

According to these results, it has been assumed that the atom consists of negatively charged electrons uniformly distributed over concentric spheres as a result of their mutual repulsion, and enclosed in a sphere of uniform positive electrification of such intensity that the electric field that would be produced outside the atom by the charges on the electrons is nullified.

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[11] J. J. Thomson, Phil. Mag., March, 1904, p. 237.

Examination of the distribution necessary for equilibrium of such aggregates consisting of consecutive numbers of electrons, reveals the following facts:

1. The distribution of one aggregate may differ from that of another in having a greater number of electrons distributed upon one or more additional concentric shells. The first aggregate has as a nucleus the identical distribution of the second.
2. The equilibrium of the distributions of some aggregates may be very stable, while that of others is less so.
3. Some less stable aggregates will become more stable if one or a few electrons be added to it. thereby giving the atom which it represents a negative resultant charge.
4. Some less stable aggregates will become more stable if one or a few electrons be taken away from it, thereby giving the atom which it represents a positive resultant charge.

Assuming the atoms of the various chemical elements to be thus constituted, the equilibrium requirements will explain their physical and chemical differences and similarities. The different aggregates indicated in (1) would yield atoms of similar qualities, but different atomic weights, as lithium, sodium, and potassium. If an atom, consisting of an aggregate whose equilibrium would be rendered more stable by the losing of one electron, should be brought up to an atom requiring for stability an additional electron, a transfer of one electron would account for known facts. The first atom would afterwards have a resultant positive charge. The second atom would have a resultant negative charge, and the two would attract each other. The first atom would correspond to an electropositive atom, like that of sodium, and the second atom would be electro-negative like chlorine. After the change and resulting attraction, a molecule of sodium chloride is formed. Chemical affinity is thus considered to be due to electric attractions.

The number of electrons in an atom may vary from time to time, and the atom may therefore have a positive or negative electrification or may be neutral. The combination of two or more atoms, that are held together by electric attractions resulting from differences in the sign of their electrifications, constitute a molecule. The atoms may be of the same or different chemical elements.

If stable equilibrium is obtained by the loss of one and only one electron, the aggregate gives an atom that is univalent and electro-positive; if a single additional electron is required for stability the atom is univalent and electro-negative. The requirement of a loss or gain of two, three, or four electrons for complete stability characterizes the atoms as divalent, trivalent, and quadrivalent respectively.

More complex molecules, as for instance the various oxides of lead, result in some cases in an incomplete stability of the component atomic aggregates.

The electrons in the atom are supposed to be moving continuously in orbits, subject to displacement and distortion under certain circumstances. The large number of electrons and their entanglement with the ether has been offered as an explanation of the spectra characteristic of different substances, which are in some cases very complex.

Some aggregates are stable when the electrons move in their orbits with an angular velocity greater than a certain value and they become unstable when the velocity falls below this value. Electron velocities decrease very slowly as a result of the loss of energy which they radiate. When, however, the critical velocity is reached, an entirely new distribution may take place, and may be accompanied by ejection of some electrons from the atom. This is possibly what takes place in the case of radium.

As a consequence of the results obtained by Thomson,[12] in 1904, concerning the structure of the atom, many have concluded that an atom of hydrogen contains over a thousand electrons and that its mass is equal to the sum of the masses of the electrons. It, therefore, has no true mass, but merely an electromagnetic mass. They have also concluded that atoms of other atomic weights contain a proportionally larger number of electrons. Such an atomic structure would satisfactorily explain differences in the atomic weights and might lead to some conclusions explanatory of characteristic spectral complexities. Thomson, however, has more recently[13] concluded from experiments upon the dispersion of light in gases, upon the scattering of Röntgen radiation in gases, and upon the absorption of β rays from radium compounds that "the number of corpuscles (electrons) is not greatly different from their atomic weight." He finds from the dispersion due to hydrogen that a hydrogen atom contains not far from one electron and that the mass of the carrier of positive electrical charge is large compared with that of the electron. From the scattering of Röntgen radiation in air he calculates that there are 25 electrons in a molecule of air.

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[12] Thomson, Phil. Mag., Vol. 7, No. 39, p. 237-265, March, 1904.

[13] Phil. Mag., p. 769, May, 1906.

The Ion. An important part is played in the phenomena of electrophysics by atomic aggregates of electrons that exhibit an external electrical field. When an aggregate or system of aggregates with an excess of positive or negative electrification is subjected to the influence of an auxiliary electric field, it tends to move in the same or opposite direction to that of the lines of force of this auxiliary field, according to the sign of its excess of electrification. It may then be termed an ion, positive or negative according to the sign of its excess of electrification. In the various physical states of matter are present the following:

NEGATIVE IONS

1. Isolated and free electrons.
2. One or more electrons acting as a nucleus for a cluster of molecules, the cluster roughly estimated, in some cases, as containing 30 molecules.
3. Atoms of electro-negative elements, the instability of whose aggregate has been reduced by the addition of one or more electrons.

POSITIVE IONS

1. Atoms of electro-positive elements, the instability of whose aggregate has been reduced by the subtraction of one or more electrons.
2. Molecular clusters from which an electron has been removed.

Negative ions may or may not be associated with ordinary matter. Positive ions are always found associated with it.

The lines of force of the electric field of an isolated ion are directed radially towards it as a center. In a molecule, while practically all the lines of force start from its electro-positive atoms and terminate upon its electro-negative atoms, thus being electrostatically nearly saturated, the field distribution is different for different planes passed through its molecular center. The molecule does not, therefore, suffer translation when placed in an auxiliary electric field, but rotates and orients itself. The orientation of a system of molecules produces a polarization of the substance containing the system.

Free electrons exist in gases at pressures under 10 mm. of mercury, especially when subjected to ionizing agencies; in conducting solids; in the β rays from radium; and in conducting flames.

Clusters exist in all conducting gases under pressures greater than 10 mm. of mercury; sometimes in gases at lower pressures, and possibly in liquids and solids.

Electronized or deelectronized atoms, or both, exist in all conducting gases at all pressures; both exist in liquid electrolytes, in solid conductors, and possibly in solid dielectrics.

The Production of Ions, or Ionization. In all gases at ordinary atmospheric pressures, spontaneous ionization is continually going on. This doubtless results from molecular collisions of an intensity much above the average. Recombination of positive and negative ions is also continually going on and will be discussed later. If an ionized gas of volume V cm^3 be enclosed in a receiver provided with two electrodes connected to the terminals of a source of electromotive force, an electric current can be made to flow through the gas and circuit. Under the influence of the electric field set up between the electrodes, the negative ions move towards the anode and the positive ions towards the cathode. A negative ion upon reaching the anode gives up to it an electron with its charge of 1.1 10^{-19} coulombs. The ion thus becomes transformed into an ordinary atom. What the anode does with the electron need not concern us at this point. In a like manner, the positive ion upon reaching the cathode receives from it an electron and itself becomes an ordinary atom. The double exchange is accompanied by what is generally understood as the conduction of 1.1 10^{-19} coulombs through the gas. It is also accompanied by the disappearance from the gas of one positive and one negative ion. If an increased voltage be employed, the velocity of the ions will increase, the current or rate of transference of electric quantity will increase, and the rate of disappearance will increase. The last can never be made to exceed the rate of production of ions. Therefore, a limiting saturation current is reached, which cannot be exceeded even though the voltage impressed upon the electrodes be increased so long as this increase does not of itself produce ionization. Spontaneous ionization of gases at ordinary atmospheric pressure will permit the passage of only about 3.3 10^{-18} amperes per cubic centimetre.[14]

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[14] Wilson, Proc. Camb. Phil. Soc. x; p. 32, 1900; Proc. Roy Soc. lxviii, p. 151, 1901.

Recombination of ions occurs in gases at a rate proportional to the square of the number present. If N ions per cm^3 be present at a given time, then the number n present after t seconds will be

$$n = \frac{N}{N\,\alpha t + 1} \tag{19}$$

where α is a coefficient of recombination, which equals[15] $1.1\ 10^{-6}$ and has the same value for hydrogen, carbon dioxide, air, and probably other gases. Its value is independent of pressures above $\frac{1}{8}$ atmospheric, but decreases with decrease of pressures below this limit.

It has been determined by Townsend that an electron, moving in a rarefied gas along a free path whose terminal points differ in potential from each other by 20 volts, *i.e.*, 20/300 electrostatic units, acquires just sufficient energy to ionize a molecule with which it comes into collision. The energy required for the production of one negative and one positive ion from a gas molecule is therefore equal to the product of this potential drop by the charge on the electron, that is,

$$\frac{20}{300}\ 3.4\ 10^{-10} = 2.3\ 10^{-11}\ \text{ergs.}$$

The velocity v acquired by the electron of mass m just before collision, is derived from the equation of energy $\frac{1}{2}\,m\,v^2 = 2.3\ 10^{-11}$, and is

$$v = \sqrt{\frac{4.6\ 10^{-11}}{m}} = 2.7\ 10^{8}\ \text{cm/sec} \tag{20}$$

This velocity is very great as compared with the mean molecular velocity of gases at ordinary temperatures. In weak electric fields, the electrons or negative ions, but not the positive ions, produce fresh ions by collision. In strong fields, both negative and positive ions produce them.

Salts introduced into the flame of a Bunsen burner are ionized and the flame becomes conducting Hot metals ionize the gas in contact with them and eject negative ions from themselves. A temperature of 200° cent. is sufficient to produce some ionization. Platinum[16] at 1500° cent. in a vacuum permits a maximum current towards it, by means of negative electrons which it throws off, amounting to one milliampere per square centimetre. Heated carbon filaments have been found to supply sufficient ions to allow of one ampere per square centimetre of surface.

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[15] Townsend, Phil. Trans A., 193, p. 129, 1900.

Gaseous ions are also produced as a result of energy expended by radioactive substances, as by X-rays, by Lenard rays, by ultraviolet light, and likewise by chemical action.

Metallic Conduction of Electricity. Investigations concerning the nature of the process of electric conduction in metals have led to the conclusion that in the metals are to be found molecules and atoms of the metallic element, positive ions, and free electrons. The molecules and atoms are not free to migrate from one part of the metal to another, but have a limited freedom of movement about a mean position. The electrons are not constrained to any particular part of the metal, but are free to move from one part to another, such movement being accompanied by collisions and changes in the direction of movement, in a manner similar to that accompanying the movement of molecules in a gas, considered from the standpoint of the kinetic theory of gases. The positive ions have been supposed by some to change their positions, by others not. The number of free electrons per cubic centimetre of metal is very large, being of the order of a billion billions. The mean free path of an electron scarcely exceeds one millionth of a centimetre in any case. The number per cubic centimetre and the length of free path are different with different metals. In an ordinary metal at a uniform absolute temperature of T degrees, all the particles of the metal are in motion, collisions are constantly occurring, and the directions of the motion are such as result from chance. According to the doctrine of the equipartition of energy, the mean kinetic energies of the molecules, of the atoms, of the positive ions, and of the electrons, are equal to each other and dependent upon the absolute temperature. Inasmuch as the masses of the electrons are much smaller than those of the other particles, the velocities of the electrons must be much greater.

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[16] O. W. Richardson, Proc. Camb. Phil. Soc., xi, p. 286, 1902.

Following Drude,[17] assume a metallic conductor of unit cross-section, and length L cm's., containing N electrons per cubic cm. each of mass m and with a charge of e_s electrostatic units. If a difference of potential V in electrostatic measure be established between the ends of the conductor, the electrons will be subjected to the influence of an electric field of intensity $E = V/L$ and, during the interval of time τ between collisions, they will be subjected to a force in the direction of the length of the conductor such that

$$m \frac{d^2 L}{d \tau^2} = E\, e_s \text{ dynes.} \tag{21}$$

Integrating throughout the time τ and evaluating constants,

$$m\, L = \tfrac{1}{2}\, e_s\, E\, \tau^2 \tag{22}$$

The electrons, if the difference of potential be maintained, will in addition to their original undetermined velocities have a velocity component v_L in the direction of L such that

$$v_L = \tfrac{1}{2}\, e_s\, E \frac{\tau}{m} \tag{23}$$

A quantity of electricity will pass per second through a cross-section of the conductor, which constitutes a current I_S in electrostatic units, such that

$$I_s = e_s\, N\, v_L = \tfrac{1}{2}\, e_s^2\, N \frac{\tau}{m} E = \tfrac{1}{2}\, e_s^2\, N \frac{\tau}{m} \; \frac{V}{L} \tag{24}$$

The resistance per unit length, that is the resistivity of the metal, will, in electrostatic units, be

$$\rho = \frac{V}{L I_s} = 2 \frac{m}{e_s^2\, N\, \tau} \tag{25}$$

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[17] Drude, Trans. Int. El. Cong., 1904, Vol. 1, p. 319.

The specific electric conductivity will equal the reciprocal of the expression or

$$\sigma = \tfrac{1}{2}\, e_s^2\, N \frac{\tau}{m} \tag{26}$$

It is desirable to substitute for τ another expression, which takes into account the mean velocity, v, of the electron in the direction of its path and the average length λ of its free path. Since $v\,\tau = \lambda$

$$\sigma = \tfrac{1}{2}\, e_s^2\, N \frac{\lambda}{v\, m} \tag{27}$$

Metallic Conduction of Heat. It is probable that the flow of heat in metal under maintained difference of temperature is due to the presence of electrons in the metal, they acting as carriers and distributors of energy which they possess in the kinetic form. According to the kinetic theory of gases, every molecule or particle possesses an average kinetic energy h at an absolute temperature of T such that

$$h = \alpha\, T, \tag{28}$$

where α is a universal constant which has a value of 1.6×10^{-16} ergs per absolute degree. If metals be ultimately constituted as has been assumed, then an electron, when uninfluenced by electric or magnetic forces, has the same energy as a gas molecule at the same temperature.

From the kinetic theory of gases, an expression for the heat conductivity of the metallic conductor, considered above, may be obtained. If one end of it be heated, the flow of energy or heat Q per second in the direction of its length and across any transverse cross-section of the conductor is given[18] by the equation

$$Q = \frac{v\, \lambda\, N}{3} \;\; \frac{d\,h}{d\,L} \text{ erg/sec.} \tag{29}$$

Substituting the value of h from (28),

$$Q = \tfrac{1}{3}\, \alpha\, v\, \lambda\, N \frac{d\,T}{d\,L} \tag{30}$$

The heat conductivity k of the metal in mechanical units, that is, in ergs per square centimetre per absolute degree per centimetre, is obtained by reducing the temperature gradient dT/dL to unity. The expression is then

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[18] Drude, l. c., p. 321.

$$k = \tfrac{1}{3}\,\alpha\, v\, \lambda\, N \tag{31}$$

It has long been known that with some exceptions the heat and electrical conductivities of pure metals, when at proper temperatures depending upon the metal, bear a constant ratio to each other. This is the law of Wiedemann and Franz. No satisfactory explanation for the constancy has been given except that which assumes that both electricity and heat are conveyed by electrons, the one under the influence of electromotive force and the other under the influence of thermomotive force. Dividing (31) by (27) and substituting $2\,\alpha\, T$ for $m\, v^2$

$$\frac{k}{\sigma} = \frac{4}{3}\left(\frac{\alpha}{e_s}\right)^2 T \tag{32}$$

The following table of Jaeger and Disselhorst[19] gives the values of k/σ at 18° cent., at 100° cent., and the ratio of the latter to the former. In this table is also given the number of electrons N per cubic centimetre, calculated by Drude[20] from data concerning the optical behavior of metals, and the mean length λ of their free path.

Metal	$k/\sigma\ 10^{-8}$ (18°)	$k/\sigma\ 10^{-8}$ (100°)	$\frac{k/\sigma\ (100°)}{k/\sigma\ (18°)}$	$N\ 10^{-22}$	$\lambda\ 10^6$ cm
Aluminum....	636	844	1.32	14.	0.2
Copper.......	665	862	1.30	4.09	1.1
Silver........	686	881	1.28	6.35	0.9
Gold.........	727	925	1.27	4.36	0.9
Nickel........	699	906	1.30	9.21	0.08
Zinc..........	672	867	1.29	18.4	0.08
Cadmium.....	706	905	1.28	11.9	0.1
Lead.........	715	935	1.31	11.2	0.034
Tin..........	735	925	1.26	14.3	0.05
Platinum.....	753	1013	1.35	13.65	0.06
Palladium....	754	1017	1.35		
Iron.........	802	1061	1.32	14.6	0.05
Bismuth......	962	1077	1.12	10.8	0.007
Antimony....				26.	0.006

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[19] Jaeger and Disselhorst, Berliner Berichte, 38, 1899, p. 719.

[20] Drude, l. c., p. 327.

That k/σ is directly proportional to the absolute temperature is clearly indicated by the values given in the fourth column of the table. The coefficient $\frac{1}{273}$, common to gases, would give, for the temperature difference here employed, viz., $100° - 18° = 82°$, the value 1.28.

The specific heats of metals are not so large as might be expected with such a large number of free electrons per unit volume.

To meet this difficulty, Thomson[21] assumes that the electrons are not free for a sufficiently long interval to acquire the energy corresponding to a given temperature. They suddenly shoot out from one atom into a neighboring one. On this basis, he calculates the values of k/σ and finds a difference of but about 12% from Drude's values.

Contact Electromotive Force. If two metals, having N_1 and N_2 free electrons, respectively, per cubic centimetre, be placed in contact with each other, and if $N_2 > N_1$, and the temperature be constant and uniform, then, according to the principles of the kinetic theory of gases, more electrons will pass from the latter into the former than in a reverse direction. This will give a negative charge to the former, and will thereby set up an electric field, whose lines of force will be perpendicular to the plane of separation; which will tend to reduce the velocity of the electrons entering the former and increase the velocity of those leaving it. An equilibrium will eventually result when as many electrons pass in one direction as in the other.

A contact difference of potential, of a value which can be predetermined if N_1 and N_2 be known, is established across the surface of separation. Drude[22] has derived an expression for this contact e.m.f., which at 18° cent. reduces to the form

$$E = 0.05 \log_\varepsilon \frac{N_2}{N_1} \text{ volts} \tag{33}$$

For other uniform temperatures, the value of E varies directly with the temperature expressed in absolute degrees. The complete expression for E is

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[21] Report of Lecture before I. E. E., Electrical Engineering, Feb. 28, 1907, p. 381.

[22] Drude, l. c., p. 323.

$$E = \frac{4}{3} \; \frac{\alpha}{e_m} T \log_\varepsilon \frac{N_2}{N_1} 10^{-8} \text{ volts} \qquad 34)$$

where α is the thermodynamic constant, e_m the charge of an electron in electromagnetic units, and T is the absolute temperature.

Seebeck Thermal Electromotive Force. If a circuit be formed of two metals connected in series, and if the difference in temperature between its two junctions be $d\,T$ absolute degrees, then the thermal electromotive force $d\,E$ set up as a result, is obtained by differentiation of (34) and equals

$$d\,E = \frac{4}{3} \; \frac{\alpha}{e_m} d\,T \log_\varepsilon \frac{N_2}{N_1} 10^{-8} \text{ volts,} \qquad (35)$$

from which the value of the thermoelectric power can be obtained. This expression assumes that N_2/N_1 does not vary with T, concerning which there is as yet not sufficient experimental evidence.

From equations (34) and (35), an expression is readily obtained for the rate of absorption or development of heat when a current I (amperes) flows in the circuit. This power P, which is a measure of the Peltier effect, is expressed as follows:

$$P = E\,I = \frac{4}{3} \; \frac{\alpha}{e_m} I\,T \log_e \frac{N_2}{N_1} 10^{-8} = I\,T \frac{d\,E}{d\,T} 10^{-8} \text{ watts.} \qquad (36)$$

Drude has also obtained an expression for the Thomson effect, that is, the development or absorption of heat as the result of a current that flows through a homogeneous circuit having local temperature differences.

Electromagnetically Induced Electromotive Force. The generation of electromotive force as a result of the relative motion between a conductor and the flux of a magnetic field is a direct consequence of the ether entanglement with the electron. A force acts directly on each electron whose direction is determined by the directions of the flux and of the motion, and whose magnitude depends upon the relative velocity and the flux-density.

The Hall Effect. Consider a rectangular piece of sheet metal with a current flowing along it. If the current enter by a terminal connected to the middle point of one edge of the rectangle and leave by a terminal connected to the middle point of the opposite edge, there will be a zero potential difference between two points located respectively at the centers of the remaining opposite edges. A galvanometer connected between these last two points would give no deflection. If now a magnetic flux be passed perpendicularly through the surface of the sheet, a current will flow through the galvanometer circuit, whose magnitude will be directly proportional to the strength of the original current and to the flux-density of the magnetic field, and whose direction will be reversed if the direction of

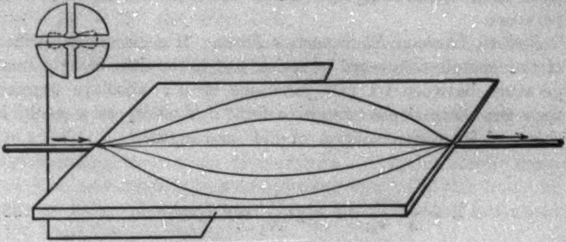

Fig. 3.—Flow lines of current.

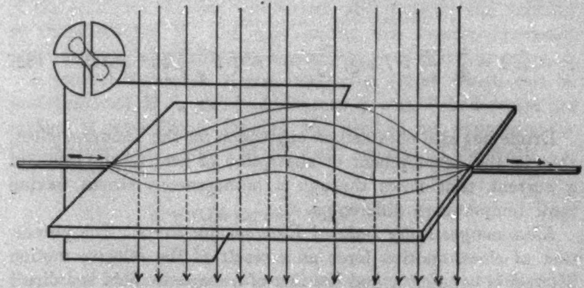

Fig. 4.—The Hall effect.

either the flux or of the original current be reversed. This phenomenon is known as the Hall effect. This effect is readily explained from the standpoint of the electron theory.

The electric current may be considered as accompanied by a procession of electrons moving in the sheet in a direction opposite to that of the current flow. Let the migration velocity of the electrons be v cm./sec., the charge of each be e_m electromagnetic units, and the magnetic flux-density be H, a transverse force F will be exerted upon each electron whose value will be $e_m\, v\, H$ dynes; and in consequence they will be forced towards one side of the sheet, and a flow of current through the galvanometer circuit will be necessary to maintain equilibrium. If no galvanometer circuit be present, a negative charge will appear at the side towards which the electrons move, and will grow until the transverse electric field which it occasions attains such an intensity E, in electromagnetic units, as to exert a force $e_m\, E$ dynes upon each of the electrons equal in magnitude and opposite in direction to that exerted by the magnetic field. Then

$$e_m\, E = e_m\, v\, H$$

Since e_m is known and E and H can readily be obtained by experiment, it is possible to obtain the average migration velocity v of an electron from the above formula, as

$$v = \frac{E}{H} \tag{37}$$

Boltzmann calculated v for various metals several years ago. The velocities are remarkably small for even very strong currents. Lorentz[23] gives the following values for one ampere flowing through a wire of one square millimetre cross-section: copper 0.005, nickel 0.2, and bismuth 90 cm./sec.

Some experimental results obtained in this field are not easily explained. The direction of the current in the galvanometer circuit, when an iron sheet is employed, is opposite to that which is to be expected. A thorough investigation of the Hall effect in ferromagnetic substances may shed some light upon the question of the cause of their large permeability. Thomson[24] explains the apparently inconsistent results by the assumption of a gyrostatic action of the molecule which causes the electrons to move in a different direction from that of the force exerted upon them by the magnetic field.

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[23] Lorentz, l. c., p. 588.

[24] Electrical Engineering, Feb. 28, '07.

Solid Dielectrics. Solid dielectrics probably contain some free electrons, although the number per unit volume is small compared with that in metals. To free electrons is due the conductivity of solid insulators that remains after surface leakage has been prevented. Free atomic ions are probably absent, since conduction through their mediation would result in a transport of matter with accompanying differences in the chemical and physical character of the surface layers of the dielectric when kept between conductors having a maintained difference of potential. Such transport has not been observed. If the atomic ions of a dielectric are not possessed of freedom of migration, the maintenance of a mean position of equilibrium must be due to the attractions and repulsions of unlike and like charged particles. If a distinction is to be drawn between atomic ions devoid of freedom of migration and molecular aggregates of atoms, then the latter are probably also present.

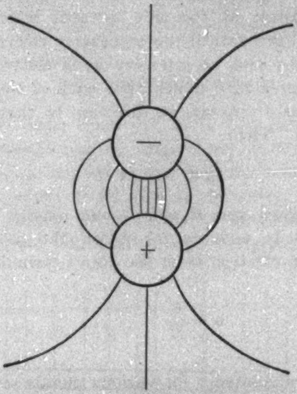

Fig. 5.—Dumb-bell molecule.

Consider a diatomic molecule in a solid dielectric. Although nothing is known of the shape of a molecule, and although in the treatment of the kinetic theory of gases it is frequently assumed to be spherical, it seems reasonable to assume, from the standpoint of the present discussion, that it is not spherical and that it may be shaped somewhat like a dumb-bell with an atom at each end connected by a sheaf of electrostatic flux lines. Such a molecule would behave in an electric field much as would a magnetic needle of the same shape in a magnetic field. Both would orient themselves, but would not suffer translation if the fields were uniform, and the molecule would have an electric moment similar to the magnetic moment of the needle. But, while the pole distance is rigidly maintained by the steel in the needle, this is not the case with the end atoms of the dumb-bell molecule. With a sufficiently large electrostatic flux-density, the molecule would be ruptured, its oppositely charged atoms being forced away from each other by the field. The rupturing of an assemblage of such molecules in a solid dielectric would, in such a field, manifest itself as a rupture of the dielectric. The molecular-magnet theory[25] of magnetic induction in iron, can, by analogy, be directly applied to solid dielectrics consisting of an aggregate of such dumb-bell molecules. The application of an electric field would orient the molecules to a greater or less extent, which would be evidenced as a residual polarization after the field was removed. Such polarization is a common occurrence. The flux due to the orientation would be superposed on the ether flux produced by the original source of the field, the dielectric thus exhibiting a larger dielectric constant than the free ether. That the dielectric constant of all solids is greater than unity is well known. Under the influence of alternating fields, the configuration of orientation would be different for the same values of increasing and decreasing intensities. This would result in a dielectric hysteresis of greater or less extent accompanied by an energy loss which would be dissipated in heat. This loss in ergs per cubic centimetre per cycle G has not only been observed, but its magnitude, as dependent upon the material and maximum electric flux-density E_{max}, is expressed by a formula[26] similar to Steinmetz's law for iron, the exponent n of E_{max} lying between 1.5 and 1.95, and corresponding to 1.6 in the Steinmetz formula. If α represent a constant dependent upon the character of the dielectric,

$$G = \alpha E^n_{max} \text{ ergs.} \tag{38}$$

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[25] Ewing, Magnetic Induction in Iron and Other Metals, p. 382.

[26] R. Threlfall, Phys. Rev., 1897, iv, p. 457; v, p. 21.

A tendency to dielectric saturation, accompanied by a reduced specific inductive capacity corresponding to the saturation and reduced permeability in iron under increase of electric flux-density, has been observed in the case of crown glass, guttapercha, megohmit, and paraffined paper.[27]

The lack of rigidity of connection between the atoms of a dumb-bell molecule permits vibration of the atoms about a mean position relative to each other. There is a natural period for such vibrations. If now an alternating electric field of this natural period be impressed upon the molecule, an interatomic vibration would be started at the expense of energy supplied by the field. The natural frequency is very large, of the order of those due to light disturbances. The propagation of light disturbances is always accompanied by an alternating electric field of high frequency. If now light, of such color as to have a frequency synchronous with the natural frequency of vibration of the atoms of the dumb-bell molecule, be passed through a transparent dielectric containing such molecules, its velocity therein would be reduced below that which would exist for higher or lower frequencies, and a prismatic spectrum, produced by passing white light through a prism of such dielectric, would therefore show the colors in other than their usual order, that is, the prism would cause what is termed anomalous dispersion. The natural frequency of vibration of quartz molecules is such that radiations of wave-lengths much longer than those of red light ($\lambda = 56\,\mu$) are refracted by a quartz prism more than violet light.[28]

The argument outlined above applies equally well to molecules of greater atomicities and complexity. It is also applicable to the negatively charged electrons and positively charged remainders of atoms, if it be assumed that these can be separated under the action of an electric field. Such an assumption is made by J. J. Thomson.[29]

The Production of Light. Many efforts have been made to explain the characteristic spectra of the various chemical elements from the standpoint of the electron theory. For many reasons, such efforts can hardly be considered as successful, as clearly presented by Crew.[30] There is as yet too little knowledge concerning the relations which exist between electrons and atoms as they occur in the various forms of matter. Furthermore, hardly anything is known about the positively electrified portion of matter or about positive electricity itself. This much, however, can be considered as established; that an electron with its negative charge e_m, when accelerating a cm/sec.^{2} the velocity of propagation of ether disturbances being c cm./sec., radiates energy into space whose value (see equation 5) is expressed as

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[27] J. A. Fleming, Electric Wave Telegraphy, p. 137.

[28] Rubens and Aschkinass, Wied. Ann., 67, p. 459, 1899.

[29] J. J. Thomson, Phil. Mag., May, 1906.

[30] Henry Crew, Science, N. S., Vol. XXV, No. 627, p. 1-12, Jan. 4, 1907.

$$J = \frac{2}{3}\frac{e_m{}^2\, a^2}{c} = 2.7\times 10^{-49}\, a^2 \text{ erg/sec} \tag{39}$$

If by any means the sign of acceleration be changed periodically at a constant frequency having a value lying between 4×10^{14} and 8×10^{14}, then the radiant energy will consist wholly of monochromatic light radiation. Change in sign can be obtained either by reversing the direction of motion in a rectilinear path with accompanying changes in velocity (collision or impact), by merely changing the direction of the path (circle) leaving the velocity unchanged, or by both. If on the other hand the duration of the periods between reversals be variable within wide limits, then there will be non-luminous heat radiation, continuous spectrum luminous radiation, and ultraviolet radiation. In this case only a portion of the energy which is radiated is converted into light.

The acceleration which an electron may assume, varies over very wide limits. When it is considered that, within a vacuum tube of a few centimetres length, an electron can start from rest and attain a velocity of one-tenth that of light, that is, $3\ \ 10^{9}$ cm/sec, its acceleration must have been at least $2\ \ 10^{17}$ cm/sec The distribution of voltage in such tubes would indicate that its acceleration near the cathode would be many times greater than this. Assuming it to be five times as great; that is, $a^2 = 10^{36}$ cm/sec^2, this electron would radiate $2.7\ \ 10^{-13}$ erg/sec or $2.7\ 10^{-20}$ watt.

Black-Body Radiation. According to the Stefan-Boltzmann[31] law, a black body (one which absorbs all radiations falling on it and which neither reflects nor transmits any) at an absolute temperature of T degrees, radiates from each square centimetre of its surface an amount of energy[32]

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[31] Stefan, Ber. d. k. Akad. d. Wiss., 79B., 2 Abth., 1879, p. 391; Boltzmann, Wied. Ann., 22, p. 291, 1884.

$$j = 1.71\ 10^{-5}\ T^4\ \text{erg/sec} \tag{40}$$
$$= 1.71\ 10^{-12}\ T^4\ \text{watt}$$

This radiation, at sufficiently high temperatures, consists of wave disturbances embodying all frequencies that are able to stimulate the optic nerves, besides a continuous series of frequencies in the infra-red and ultraviolet regions.

The portion, W, of the total radiation per cm^2 that is capable of stimulating the optic nerves so as to given a sensation of light is to be obtained from the equation[33]

$$W = C\left(\frac{T}{k}\right)^4 \lambda'^{-3}\ e^{-\frac{k}{\lambda' T}} \left\{\left(\frac{k}{T}\right) + 3\ \left(\frac{k}{T}\right)^3 \lambda' + 6\left(\frac{k}{T}\right)\lambda'^2 + 6\,\lambda'^3\right\}$$

$$-\,C\left(\frac{T}{k}\right)^4 \lambda''^{-3}\ e^{-\frac{k}{\lambda'' T}} \left\{\left(\frac{k}{T}\right)^3 + 3\left(\frac{k}{T}\right)^2 \lambda'' + 6\left(\frac{k}{T}\right)\lambda''^2 + 6\,\lambda''^3\right\}$$

erg/sec (41)

where $\lambda' = 0.000039$ = wave length at violet end of spectrum in cm.

$\lambda'' = 0.000075$ = wave length at red end of spectrum in cm.
$C = 1.24\ 10^{-5}$
$k = 1.4135$
$e = 2.718$ = Naperian logarithmic base.

The visible radiation efficiency at any temperature T is therefore

$$\varepsilon = \frac{W}{j} \tag{42}$$

Carbon filaments are generally considered to yield approximately black-body radiation.

The radiated energy is not equally distributed among the various frequencies. Planck[34] has shown that the energy radiated per cm^2 between wave-lengths λ and $\lambda + d\lambda$ can be represented by the equation

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[32] F. Kurlbaum, Wied. Ann., 65, 1898, p. 746; Drude, Theory of Optics, p. 515.

[33] Mendelhall and Saunders, Astrophys. Journ., 1901, p. 46.

[34] Planck, Verh. d. Deutsch. Phys. Geo., 2, 1900, p. 202; Ber. d. k. Akad. d. Wiss., Berlin, 1901, p. 544.

$$E = C\lambda^{-5} \frac{1}{e^{\frac{b}{\lambda T}} - 1} \tag{43}$$

The physiological characteristics of the normal eye are such that for different wave-lengths different rates of energy are required to be received upon the retina in order to produce the same intensity of sensation. Therefore, while values of ε indicate the stimulative portions of radiation, they do not indicate the amounts of luminous sensation that thereby might be produced. Although the sense responsiveness of the eye for a given color varies and depends on the individual, on the portion of the retina stimulated, on visual fatigue, and on the rapidity of iris response to variations in intensity, an average sensation equivalent of W can be obtained by making use of Abney's[35] coefficients of luminosity for the normal eye. With wave-lengths as abscissas, values of E are plotted as ordinates. The values of E are each multiplied by the luminosity coefficient corresponding to the wave-length and used as ordinates in plotting a new curve. If the values of λ be limited to the visible spectrum, then the area included between the first curve and the axis of abscissas is proportional to W, while the area Z between the second curve and the axis is proportional to the sensation equivalent. The luminous efficiency of the radiation is then

$$\eta = \frac{Z}{I} \tag{44}$$

As the temperature of a black body rises not only does the power radiated increase but the predominating frequency rises, that is, the wave-length λ_m at which the intensity of radiation is the greatest, decreases. At an absolute temperature[36] T

$$\lambda_m = \frac{0.2887}{T} \text{ cm.} \tag{45}$$

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[35] Abney, Color Vision, 1895.

[36] Drude, Theory of Optics, 1902, p. 523; Wien. Berl. Ber., 1893, p. 55; Wied. Ann., 49, 1893, p. 633; 52, 1894, p. 132.

The intensity of the radiation at these wave-lengths also increases as the fifth power of the absolute temperatures.

If a black body, for example, a carbon filament, be considered as containing free electrons as well as atoms and molecules, then as its temperature is raised the mean kinetic energy of each electron would be increased. Inasmuch as the geometrical dimensions of the filament are not materially altered by the change of temperature, it is reasonable to assume that the length of free path is not increased. The increase of energy, causing an increase of electron velocities, will result, therefore, in an increased frequency of collisions and an increased rate of change of velocities. This accounts for the direction of the shifting of λ_m with rise of temperature, and for the accompanying increase of total radiation. Many of the collisions will occur oftener than at the preponderating frequency, and others will occur less often, which accounts for the character of the distribution of radiated energy over a wide range of frequencies. The accelerations which accompany collisions of the higher frequencies are of necessity greater than in the case of lower frequencies. The radiated energy is therefore greater in the former case than in the latter, and the curve of distribution of radiated energy over different frequencies is not symmetrical but deviates from the curve of probabilities.

Selective Radiation. No material radiates in accordance with the laws of black-body radiation. One of the first conclusions of Maxwell's electromagnetic theory is that good conductors of electricity cannot be transparent. Hagen and Rubens[37] have shown how the absorbing power and the emissive power of metals can be calculated from their electrical conductivities. Their experimental results for the longer heat-waves are very satisfactory. Kirchhoff's law, according to which the ratio between the emission and the absorption for all bodies has the same value, being a universal function of the absolute temperature and of the wave-length, has also been accounted for from the standpoint of the electron theory. Lorentz, using the expression for the electrical conductivity previously developed [see equation (29)] has calculated the value of this function. He then compares the amount of energy radiated from a metal within the limits of certain long wave-lengths with the experimental values obtained by Lummer and others, and finds that they are in accord.

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[37] Hagen and Rubens, Ann. der Phys., 11, p. 873, 1903.

Luminescence. At all temperatures above absolute zero, all bodies radiate energy. If the nature of the body be not changed by this radiation; that is, if it continues to radiate in the same manner, as long as its temperature is maintained constant by the addition of heat, the process is termed pure temperature radiation. If, on the other hand, the body changes because of the radiation, and does not continue indefinitely to yield the same radiation although its temperature is kept constant, the process is termed luminescence. The cause of some of the radiation in the latter case does not lie in the temperature of the system but in some other source of energy. According as the extra supplied energy accompanies either chemical transformations, exposure to light, or the passage of electric currents, the processes are respectively termed chemico-, photo-, and electro-luminescence. The total radiation from a body of this class is made up of two parts, that due to its temperature and that due to the extra energy. If the intensity of radiation of a body within any region of wave-lengths is greater than that of a black-body at the same temperature, luminescence must be present. This is frequently[38] taken as a criterion for the detection of luminescence. The frequencies of luminescent radiations are more or less restricted, being often evidenced by bright-line spectral distributions. The electrons which yield these radiations are supposed to vibrate harmonically under conditions that are not yet understood. That their movements are not governed simply by chance seems to follow from the character of the spectra. Although change in the character of the material as a consequence of its yielding luminescent radiation may not be capable of detection by chemical analysis, yet the atomic and molecular systems are nevertheless doubtless undergoing constant changes due to the loss or gain of electrons. The entrance of an electron into a system, or its ejection, must without doubt occasion complex harmonic disturbances of many or all the electrons in the system.

If luminescent radiation be confined chiefly to wave-lengths of the visible spectrum, the luminous efficiency of the body becomes high. Herein rests the economic significance of the efforts being made to advance the art of lighting by means of vacuum tube and flaming arc lamps.

A very interesting example of luminescent radiation is that which is yielded by photogenic bacteria, which are frequently found in sea-water and upon meats and fish that have been directly or indirectly infected by sea-water. They are the sources of light known as the phosphorescence of the sea. Some cases of phosphorescence in animals and in plants are explained as an infection with them. Gorham[39] has shown that the light which they give is the result of chemical transformations accompanying metabolism inside the cells of their bodies. When fed with substances such as asparagin or glycocoll, they are able to grow and reproduce but not to give light. In Gorham's summary, occurs the following:

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[38] Drude, Theory of Optics, p. 528.

> We therefore conclude that for light production there must be present, over and above the requirements for growth, the oxygen of the air, *sodium or magnesium*, and certain organic acids, derived from the decomposition of the carbon and nitrogen constituent of the food.
>
> The chemical energy resulting from the union of the sodium or magnesium with these organic acids, in the presence of oxygen, or from the later combustion of the products of that union, is set free in the form of light.

The brightness of these bacteria considered as sources of light is very small. Lode's[40] measurements show an intensity of emission of 0.00060 candles per square meter. This is too small to stimulate the color sense. The *bacillus lucifer* of Molisch,[41] however, is much brighter, gives a continuous spectrum in the green, blue, and violet, and is able to stimulate the color sense.

Conclusion. Although much is known concerning the size and mass of the electron, its electric and magnetic effects when in motion, and its radiation effects during acceleration, little more is known concerning its structure than that:[42]

> It is the intrinsic strain-form alone that constitutes the electron; and it is a fundamental postulate that the form can move from one portion to another of the stagnant ether somewhat after the manner that a knot can slip along a cord.

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[39] F. P. Gorham, The Photogenic Bacteria, Doctor's Thesis, Harvard Univ., May 1, 1903.

[40] Lode, Zentralbl. für. Bakt., I 35, Bd., p. 524.

[41] Molisch, Leuchtende Pflanzen, 1904, p. 133.

[42] Larmor, Æther and Matter, 1900, p. 335.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

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THE HEATING OF COPPER WIRES BY ELECTRIC CURRENTS

BY A. E. KENNELLY AND E. R. SHEPARD

In August 1889, a report was made by one of the present writers[1] to the Edison Electric Light Co., on "The Heating of Conductors by Electric Currents." The report was published in the minutes of the convention of the Association of Edison Illuminating Companies, at Niagara Falls, August, 1889. It contained a large number of measurements of the temperature elevations of active conductors supported in wooden moulding, and in free air, within doors and without. A further report was made in 1893[2] upon the temperature elevations of electric-light cables. The research reported in the present paper has been undertaken to extend the scope of the above measurements, and also to increase the precision of the results previously obtained. In the measurements of 1889 and 1893, above referred to, the temperature-coefficient of resistivity of copper wires was taken as 0.388 per cent. per degree centigrade of temperature elevation; whereas it is now taken by the American Institute of Electrical Engineers as 0.42 per cent. per degree centigrade from and at 0° cent.[3] Again, the law of thermal radiation employed was that of Dulong and Petit;[4] whereas the law of radiation generally adopted at this time is that of Stefan.[5]

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[1] The Heating of Conductors by Electric Currents, by A. E. Kennelly, *The Electrician*, Dec. 13th, 1889, Vol. XXIV, p. 142; *The Electrical World*, Vol. XIV, No. 21, p. 336, Nov. 23, 1891.

[2] The Carrying Capacity of Electric Cables, Submerged, Buried or Suspended in Air, by A. E. Kennelly, Minutes of the Ninth Annual Meeting Association of Edison Illuminating Companies, 1893, p. 79.

[3] Trans. Am. Inst. Elect. Engineers, Vol. XIX, p. 1082, June, 1902. Standardization Report.

[4] Annals de Chemie et de Physique, 1817, Vol. VII.

[5] Wien. Akad. Ber., 1879, LXXIX, pp. 391–428.

Although these changes in physical data and constants do not greatly affect, from an engineering standpoint, the results previously obtained; yet it seemed desirable to make a new series of measurements[6] and deduce their results with the aid of the most recent data. It is the object of this paper to describe the new measurements, so far as they relate to wires in water, soil, or wooden moulding, leaving the measurements on wires in air to some future occasion.

Method of Determining Temperature Elevations. The copper conductor under test had a length of from 2 to 6 metres (6.56 to 19.69 feet). Pressure wires were soldered to it near its ends. The resistance of the conductor between these pressure wires was determined; first, when cool, *i.e.*, at the temperature of the surrounding air, and second after having been heated by an electric current of measured strength. The increase in the resistance of the conductor enabled its increase in temperature to be determined by the formula:

$$R_t = R_0\,(1+0.0042\,t) \qquad \text{ohms} \qquad (1)$$

where R_0 is the resistance of the conductor at 0° C., and R_t its resistance at t° C.

Method of Measuring the Resistance of the Copper Conductors. The resistances of the copper conductors under test were measured by a differential galvanometer; *i.e.*, by connecting one coil of a differential galvanometer to the pressure wires on the tested conductor, and the other coil to the terminal of a german-silver constant resistance of determined amount in circuit with the tested conductor. Extra resistance was inserted in the circuit of the coil of preponderating current until the galvanometer deflection was zero, or the two currents differentially balanced. Under these conditions, the resistance of the tested conductor became known in terms of the constant german-silver resistance. As the tested conductor increased in temperature, its changes of resistance could readily be observed and followed, by noting the change in the balancing resistance.

The electrical connections employed are indicated diagrammatically in Fig. 1. A separate motor-driven low-voltage direct-current dynamo Y, of 3-kw. capacity (300 amperes at

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[6] The research was carried on at Pierce Hall, Harvard University, and a report thereon formed the subject of a thesis for the degree of A.M. by E. R. Shepard, entitled: "The Heating of Copper Wires by Electric Currents." 1906.

10 volts), was connected by stout leads to the conductor *C C*, under test, in another room, through a grid resistance *D* of german-silver wires and a regulating resistance *R*. The current strength in the circuit was measured by the Weston ammeter *A*, and adjusted partly by varying the resistance *R* and partly by varying the shunt field rheostat *F*. The differential galvanometer *G* has one coil connected to pressure wires on the standard grid resistance *D*, and the other coil to pressure wires on the tested conductor *C C*. An adjustable resistance *r* was inserted in one or the other of the two galvanometer circuits as occasion required, in order to secure a differential balance. Switches in the main circuit and in the galvanometer circuits have been omitted from the diagram.

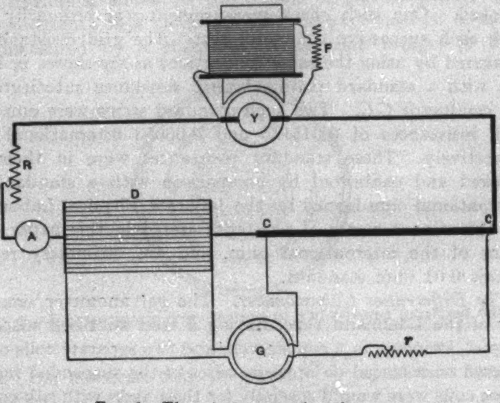

FIG. 1—Electrical connections in tests

The German-silver Wire Grid. The grid was made up in such a manner as to carry the strongest testing currents used with a relatively small rise of temperature, and was made of metal having a relatively small temperature-coefficient of resistivity, so as to maintain a practically constant resistance during the tests. It consisted of an open wooden frame about 2 metres long (6.56 feet) by 1 metre broad (3.28 feet), containing 65 parallel wires of german-silver supported freely in air, each 0.129 cm. (0.0508 in.) in diameter, and 183 cm. (6 feet) in length. These wires were divided into three permanently connected groups of 25, 20, and 20 wires respectively, in such a manner that the groups could be connected either in series or in parallel for different resistances and current-carrying capacities. When the three groups were connected in series, the total resistance of the grid between pressure wires was 0.0441 international ohm. When the three groups were connected in parallel, the resistance of the grid between pressure wires was 0.0044 international ohm. Intermediate series-parallel groupings and corresponding resistances were also used in some of the tests.

The resistance of the grid was frequently measured and checked. One such check measurement was ordinarily made with each successive conductor test. The grid resistance was measured by using the same connections as are shown in Fig. 1, but with a standard platinoid strip resistance substituted for the conductor *C C*. Two such standard strips were employed, with resistances of 0.015125 and 0.03053 international ohms respectively. These standard resistances were in their turn checked and calibrated by comparison with a standard 0.01 international ohm loaned by the Jefferson Physical Laboratory. All the measurements of resistance stated in this paper are in terms of the international ohm, and are ultimately referred to this 0.01 ohm standard.

The Differential Galvanometer. The galvanometer employed was of the Edelmann type, having a steel split-bell suspended magnet, swinging in a copper well, and two separate coils of silk-covered wire placed on opposite sides of the suspended magnet. These coils were wound specially for these tests with silk-covered copper wire, each coil having a resistance of about 1800 ohms. The resistances of the coils, being subject to change with variation of room temperature, were frequently measured during extended tests. The differential condition was also frequently checked.

The sensitiveness of the galvanometer as used in the tests was 0.143 microampere for 1 mm. scale deflection at the range used of 140 cm. Referred to a range of 1 metre, this would be 0.20 microamperes per mm. scale-reading deflection, or the current sent by 1 volt through 5 megohms, including both coils.

The periodic time of the galvanometer swing was 5.17 seconds. The damping ratio of successive opposite elongations was 2.465, or the Naperian logarithmic decrement of successive opposite elongations 0.9027. Four complete swings, executed in 20.7 seconds, sufficed to reduce the deflection to $\frac{1}{1870}$ part, or, for practical purposes, to rest.

When balance is obtained on the differential galvanometer G in Fig. 1, we have

$$x = R_D \frac{G_c + r}{G_D} \quad \text{international ohms} \qquad (2)$$

where R_D is the resistance of the grid, G_c and G_D the resistances of the two galvanometer coils respectively, including leads, and r the resistance added to the circuit of the conductor $C\,C$, whose resistance is x ohms. In all the experiments, G and r were measured by a B.A.-unit Wheatstone bridge, in B.A.

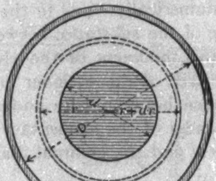

FIG. 2—Diagrammatic cross-section of lead-covered insulated wire

ohms. As, however, only the ratio $\frac{G_c + r}{G_D}$ appears in formula (2) this does not affect the evaluation of x in international ohms.

Theory of the Temperature Elevation of an Active Conductor Cooled Entirely by Thermal Conduction. The simplest case of the heating of an active electric conductor is that of a uniform cylindrical wire carrying a steady direct current, and covered with a uniform concentric coating of rubber or other insulator, the external surface of which, either with or without a leaden sheath, is kept at a uniform known temperature by being immersed in a tank of running water.

In Fig. 2, the wire of diameter d cm, is covered by insulating material to a total diameter of D cm. The external sheath of lead is so good a thermal conductor that, for all practical purposes, its temperature is t° C. at all points. The internal wire of copper is likewise so good a thermal conductor that its temperature at all points is $t+\theta$ degrees centigrade. This means that, after a sufficiently long application of a direct current through the wire to establish a steady thermal condition, there is a difference of temperature of θ° C. between the internal and external surfaces of the insulating cylinder.

If we consider one unit length or linear centimetre of the conductor, the thermal resistance, to the radial flow of heat, offered by any cylindrical element of the insulator between the radii r and $r+d\,r$ centimetres will be

$$d\,\mathcal{R} = \frac{dr}{2\,\pi\,r}\,\sigma \qquad \text{thermal ohms} \quad (3)$$

where σ is the thermal resistivity of the insulator at its working temperature, and is numerically equal to the thermal resistance of a cubic centimetre of the substance between any pair of opposed faces, dr is the thickness of the elementary cylinder, and $2\,\pi\,r$ the surface area of this cylinder in unit length. The total thermal resistance between wire and sheath will be the sum of all the resistances of the elementary cylinders between the internal diameter d and the external diameter D; or

$$\mathcal{R} = \frac{\sigma}{2\,\pi}\log_\varepsilon\frac{D}{d} \qquad \text{thermal ohms} \quad (4)$$

in a linear centimetre of the insulator.

If ρ_t is the electric resistivity of the wire at the initial temperature t° C., which is also the temperature of the external surface, the electric resistance of the wire per linear cm. is

$$R_t = \frac{4\,\rho_t}{\pi\,d^2} \qquad \text{ohms at } t^\circ \text{ C.} \quad (5)$$

and at the temperature finally reached by the wire $(t+\theta)^\circ$ C., the resistance is

$$R_{t+\theta} = \frac{4\,\rho_t\,(1+a\,\theta)}{\pi\,d^2} \qquad \text{ohms} \quad (6)$$

where a is the temperature coefficient of resistivity of the wire for the initial temperature t° C., and[7] is equal to $\frac{1}{238.1+t}$.

---

[7] The Resistivity Temperature-Coefficient of Copper. *Electrical World*, June 30, 1906.

The total flow of heat, or thermal current, passing radially through a linear centimetre of the insulator in the steady state, with a current of I amperes in the wire, is

$$\mathcal{J} = I^2 R_{t+\theta} \qquad \text{watts per cm.} \quad (7)$$

This thermal energy current follows a law similar to Ohm's law, or

$$\mathcal{J} = \frac{\theta}{\mathcal{R}} \qquad \text{watts per cm.} \quad (8)$$

and by (4)

$$\mathcal{J} = \frac{\theta}{\frac{\sigma}{2\pi} \log_\varepsilon \frac{D}{d}} \qquad \text{watts per cm.} \quad (9)$$

and by (6)

$$\frac{4 I^2 \rho_t (1 + a\,\theta)}{\pi d^2} = \frac{\theta}{\frac{\sigma}{2\pi} \log_\varepsilon \frac{D}{d}} \qquad \text{watts per cm.} \quad (10)$$

Consequently

$$\frac{\theta}{1 + a\,\theta} = \frac{2\sigma\rho_t \log_\varepsilon \frac{D}{d}}{\pi^2 d^2} I^2 \qquad \text{degrees C.} \quad (11)$$

or

$$\frac{\theta}{1 + a\,\theta} = K I^2 \qquad \text{degrees C.} \quad (12)$$

where K is a constant for a conductor of given dimensions, if the thermal resistivity σ may be taken as constant. We know that σ may vary with temperature in many substances, but there is evidence in this report to show that it is substantially constant in various insulating substances, between the limits of 0° C. and 100° C.

Equations (11) and (12) express the relation between the final temperature of any wire carrying a continuous current, under the conditions of Fig. 2. Equation (12) must apply to any uniform wire carrying a continuous current in the steady state, no matter how many successive layers of insulator there may be, provided only that the heat escapes by conduction, as distinguished from radiation and convection, and also provided that the thermal resistivities of the successive insulators may be taken as constant within the range of their working temperatures. Formula (12) applies, therefore, to all buried continuous-current cables, and also to insulated wires in water. It also applies fairly well to insulated wires in wooden moulding. It is the fundamental equation of electric heating of concealed wires, carrying continuous currents, from the temperature t° C. of surrounding objects to the final temperature $(t+\theta)^\circ$ C., when the temperature elevation θ does not exceed, say, 100° C.

The temperature coefficient a varies with the initial temperature t° C.

For an initial temperature $t = 12^\circ$ C. $a = 0.004$
" " " " $t = 18^\circ$ C. $a = 0.0039$
" " " " $t = 25^\circ$ C. $a = 0.0038$

If we take $t = 18^\circ$ C., as an average initial temperature in practice, equation (12) becomes:

$$\frac{\theta}{1+0.0039\,\theta} = K I^2 \qquad \text{degrees C.} \qquad (13)$$

This means that the final temperature elevation θ of a wire carrying a continuous current I amperes, increases somewhat more rapidly than the square of the current, and the deviation from the square is greater, the greater the temperature elevation. This relation may also be rendered evident in a graphical way as follows: Logarizing both sides of (13), we have

$$\log \theta - \log (1+0.0039\,\theta) = 2 \log I + k \qquad (14)$$

where $k = \log K$, and is a constant for a given size of wire and succession of insulating coatings.

If we plot $\log I$ (Fig. 3) against $\log \theta$, we draw the straight line $e\,f$, making with $e\,x$ an angle 63° 26′ whose tangent is 2. This represents the locus of $\log \theta$. We then lay off a curved line $A\,B\,C\,D$, such that its distance from the straight line $E\,F$ is everywhere $\frac{1}{2} \log (1+0.0039\,\theta)$. By deducting these distances from $e\,f$, we obtain the final curve $a\,b\,c\,d$, which, by (14), is the graph of $\log \theta$ in relation to $\log I$. Joining the points a and d by the broken straight line $a\,d$, we find that this is inclined to the $e\,x$ axis by an angle whose tangent is 2.289; so that the final temperature elevations of 10° and 100° C., in accordance with (13), represent an increase of temperature in the ratio of $I^{2.289}$, or the exponent of 2.289 for the currents.

In other words, judging from these two observations alone, it would appear that the temperature increased as the 2.289th power of the current. If, however, we consider the points *a* and *c* on the curve, corresponding to the temperature elevations 10° and 50° C. respectively, the dotted straight line *a c* makes with *e x* an angle whose tangent is 2.19. This represents an increase of temperature elevation according to $I^{2.19}$, so far as concerns these particular points.

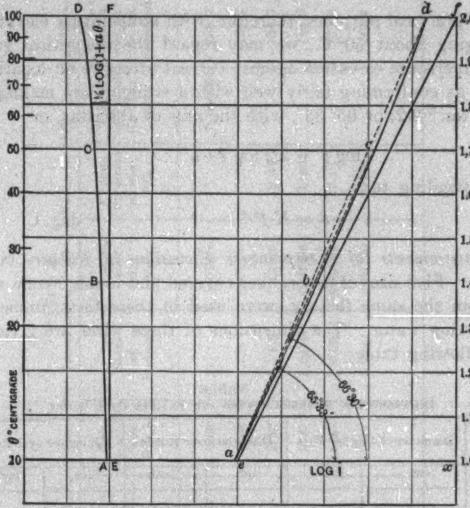

FIG. 3—Diagram indicating the graphical relation between current and temperature elevation when plotted on logarithm paper

If then we plot log θ against log I, in accordance with (13) and (14), the graph will be a flat curve commencing at an angle $\tan^{-1} 2$, and bending slowly upward in such a way that, on the 10°–50° range, θ varies approximately as $I^{2.3}$; whereas taking the 10°–100° range, θ varies approximately as $I^{2.3}$. The exact value of the exponent will depend both on t and on θ If we limit our enquiry to temperature elevations of 50° C., we may expect to find the observations on logarithm paper fall nearly on a straight line, making an angle $\tan^{-1} 2.2$ with the axis of abscissas. If, however, we extend the range of observation to $\theta = 100°$ C., the mean straight line on logarithm paper will be somewhat steeper, and approach the angle $\tan^{-1} 2.3$.

Thus if $t = 6°$ C. $\theta \propto I^{2\cdot304}$ between $\theta = 10$ and 100° C.
if $t = 12°$ C. $\theta \propto I^{2\cdot296}$ " " = " " "
if $t = 18°$ C. $\theta \propto I^{2\cdot289}$ " " = " " "
if $t = 25°$ C. $\theta \propto I^{2\cdot282}$ " " = " " "

For practical purposes, therefore, with temperature elevations averaging about 50° C., we may regard the theoretical graph of temperature elevation against current strength on logarithm paper as conforming fairly well with a straight line making an angle $\tan^{-1} 2.2$, or 65° 33′, with the axis of abscissas, or

$$\log \theta = 2.2 \log I + k \qquad (15)$$

corresponding to

$$\theta = K I^{2\cdot2} \qquad \text{deg. C.} \qquad (16)$$

Measurements of Temperature Elevation in Rubber-Covered Wires. Five sizes of new rubber-covered and braided code wire, all from the same factory, were used in these tests, immersed in running water. The dimensions of these wires are given in the following table:

TABLE I
DIMENSIONS OF RUBBER-COVERED AND BRAIDED CODE WIRES

Size of Wire A. W. G.	Diameter of Copper Wire		Diameter over Rubber		Diameter over Braid	
	cm.	Inch	cm.	Inch	cm.	Inch
8	0.3263	0.1285	0.6348	0.25	0.7365	0.290
10	0.2552	0.1005	0.4952	0.195	0.6223	0.245
12	0.2032	0.0800	0.432	0.170	0.5715	0.225
14	0.1626	0.064	0.3987	0.157	0.482	0.190
16	0.1296	0.051	0.2895	0.114	0.381	0.150

A length of about 5 metres of each of the above wires had pressure wires soldered to the conductor, and was then immersed in running water during the test. The time required to attain a practically steady temperature after the application of a continuous current was only about 5 minutes under these conditions. Table II gives the recorded observations in the case

TABLE II.

TESTS OF No. 16 A. W. G. RUBBER COVERED AND BRAIDED WIRE IMMERSED IN RUNNING WATER AT 5° C. DISTANCE BETWEEN PRESSURE WIRES 550 CM.

Time from Start, min.	Current Strength, amp.	Res. of Galvr. Coils B.A.U.		Res. added to wire B.A.U.	Ratio of Increase	Res. of wire Int. ohms.	θ Temp. Elevation of wire. °C.	Res. of Standard Grid Int. ohms	$R_{t+\theta}$ Res of wire per cm. Int. microhms	I watts per cm. $I^2 R_{t+\theta}$	$\frac{\theta}{I}$ Thermal Res. of linear cm.	t Temp of water °C.
		C	D									
0	3	1776	1853	1200	1.	0.07081		0.04409	128.7			5
7	30	"	"	1292	1.031	0.07300	7.54	"	132.7	0.1194	63.15	"
15	35	"	"	1330	1.0435	0.07390	10.58	"	134.3	0.1645	64.31	"
22	40	"	"	1370	1.0570	0.07486	13.86	"	136.0	0.2176	63.69	"
26	45		"	1420	1.0738	0.07604	17.04	"	138.2	0.2799	64.09	"
33	50	"	"	1477	1.0930	0.07740	22.61	"	140.7	0.3517	64.27	"
										Mean =	63.9	

of the No. 16 wire, and is a fair example of the measurements taken collectively. The second column gives the current strength steadily applied. The initial balance was obtained by a brief application of a current of 3 amperes. A current of 30 amperes was then applied at the start and the balance again observed after 7 minutes. The current was then increased to 35 amperes for 8 minutes, and so on.

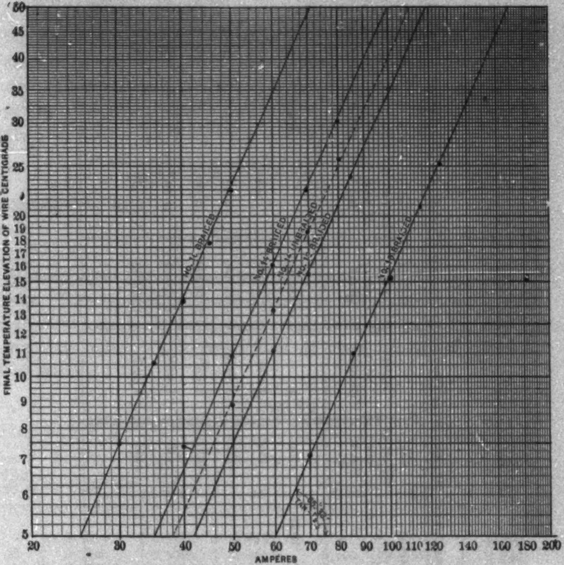

FIG. 4—Observed temperature elevations of different sizes of code rubber-covered wires in water

The last column but one gives the thermal resistance of a linear centimetre of dielectric and braid. Its mean value is 63.9 thermal-ohm-cm.

The temperature elevations θ in the above table are plotted as black circles in Fig. 4 on logarithm paper. The straight line, marked No. 16 braided, is drawn through the 30-ampere point to make an angle of 65° 33′, or $\tan^{-1} 2.2$, with the axis of abscissas. This straight line corresponds, therefore, to formulas (15) and (16) derived from the theory already outlined. The agreement of the observation points with the theoretical straight line is seen to be satisfactory.

Table III contains all the final temperature elevations computed from the measurements made on the samples of wire scheduled in Table I, and also contains the corresponding thermal resistances in one linear centimetre. The final temperature elevations are all plotted in Fig. 4 as ordinates, against currents as abscissas, to logarithmic scales, the straight lines being drawn parallel to each other according to formulas (15) and (16). With the exception of one doubtful observation on the No. 14 braided wire, all the points are in satisfactory conformity with these parallel straight lines, thus confirming the theory already outlined, as expressed in formulas (11), (12), (13), and (14).

TABLE III

TEMPERATURE ELEVATIONS OF DIFFERENT SIZES OF RUBBER-COVERED WIRES IN WATER

Current Amp.	I No. 16 Braided $t=5^\circ$		II No. 14 Braided $t=5.5^\circ$		III No. 14 Unbraided $t=5^\circ$		IV No. 12 Braided $t=4.5^\circ$		V No 10 Braided $t=4.5^\circ$	
	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.	θ Temp. Elev.	$\mathcal{R}$ Thermal Res.
30	7.54	63.15								
35	10.58	64.31								
40	13.86	63.69	7.4							
45	17.94	64.09								
50	22.61	64.27	10.91	52.88	8.8	42.93				
60			16.22	53.47	13.3	44.31	11.16	59.45		
70			22.46	53.12	18.6	44.56	15.43	59.37	7.16	45.8
80			30.32	53.17	25.86	46.15				
85							23.77	60.11	11.11	47.46
100							35.16	61.59	15.26	46.32
115									20.86	46.87
125									25.13	47.03
Means		63.90		53.21		44.50		60.13		46.70

A comparison of columns II and III in Table III, or of the corresponding lines in Fig. 4, shows that the addition of a coating of cotton braid about 0.4 mm. (1/64 inch) increased the temperature of the No. 14 wire about 2° C. with 50 amperes, and about 4.5° C. with 80 amperes, the wire being immersed in water in each case. The braid also added 8.7 thermal-ohm-cm. (3.76 thermal-ohm-inches) to the linear thermal resistance of the covering of this particular wire.

Taking the internal and external diameters of the braiding of No. 14 wire from Table I as 0.3987 cm. (0.157 in.) and 0.482 cm. (0.190 in.) respectively, we obtain by formula (4) the thermal resistivity $\sigma = 287.1$ thermal-ohm-cm., when soaked in water at 5° C.

With this thermal resistivity for the soaked braid, the thermal resistivity of the rubber covering on the wires was deduced, as in the following table:

TABLE IV.

Thermal Resistances and Resistivities of Wire Coverings

Size Wire A. W. G.	Thermal Resistance of Wire in a linear centimetre			Thermal resistivity	
	rubber + braid	braid	rubber	braid	rubber
	ohms-cm.	ohms-cm.	ohms-cm.	ohms-cm.	ohms-cm.
10	46.7	10.47	36.23	287.1	343.5
12	60.13	12.82	47.31	"	394.4
14	53.21	8.71	44.50		311.6
16	63.90	12.51	51.39	"	401.5
				Mean =	387.8

The mean resistivity of the " rubber " covering of these wires was therefore 387.8 thermal-ohm-cm.; but, since this material in code rubber-covered wires is largely composed of filling material other than rubber, different compositions are likely to vary considerably in thermal resistivity.

The thermal resistance $\mathcal{R}$ in a linear centimetre of any size of such braided and rubber-covered wire is readily determinable from the dimensions of the wire and the above mean thermal resistivities by the aid of formula (4), and the probable temperature elevation for a given current strength then follows from formula (8). If the wire is buried in the ground, the additional thermal resistance of the ground must be added, taking into account the heat that may be liberated by any active wires buried in the same trench or conduit.

Heating of Code Rubber-Covered Wires in Wooden Moulding. When rubber-covered wires are laid in wooden moulding, the heat generated by continuous currents in each wire has to pass in succession through the rubber, dry braiding, air-space, wooden moulding, and finally through wall, ceiling or air. Owing to the complex geometrical relations of these successive thermal resistances, they are not easy to compute, even when the thermal resistivities of the respective substances are correctly stated. The best plan is, therefore, to measure the thermal resistance of the series combinations under different conditions such as occur in practice, and then to tabulate the safe carrying capacity of such wires from the measurements directly, as in the report of 1889, above referred to.

The moulding used in the tests here reported was of pine wood, of the cross-section shown in Fig. 5. Its length was 3.86 metres (12.67 feet) and its weight was 720 gm. per metre (0.48 lb. per foot). It was lightly nailed down flat upon the wooden floor of the testing room. The wire to be tested was laid in a loop along the moulding so as to occupy the two outside grooves, as indicated in the figure, leaving the middle groove vacant. Pressure wires were connected to the test wire at points about 5 metres apart. The temperature elevation became substantially constant thirty minutes after the application of each testing current strength. The initial temperature $t°$ C. varied from 19.0° C. to 21.0° C. in the different series of tests. The results of the measurements are recorded in Table V in terms of the final temperature elevation and of the linear thermal resistance for each size of wire.

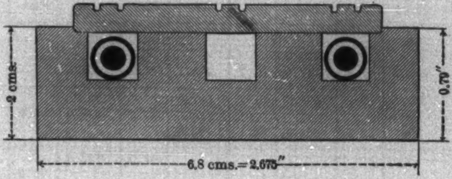

FIG. 5—Cross-section of wooden moulding

It is to be observed that the temperature elevations of these wires, whose dimensions were substantially the same as those appearing in Table I for the lengths tested in water, are more than ten times greater than those for the corresponding steady current strengths in Table III.

The linear thermal resistance of the rubber, as above deduced, is deducted in Table V from the mean linear thermal resistance of each moulded wire. The balance is the inferred linear thermal resistance in series of dry braid, air, wood, and external air. This extra linear thermal resistance steadily diminished from 466.6 thermal-ohms in one linear centimetre (183.5 thermal-ohm-inches), with No. 16 wire, to 343.9 thermal-ohm-cm. (135.3 thermal-ohm-inches) with No. 8 wire. This reduction in linear thermal resistance may be accounted for by the reduction in the thickness of the air-space between braid and wooden-moulding walls, as the size of the wire was increased. With these particular sizes of wire, composition of "rubber," size and quality of moulding, the linear thermal resistance of the entire series was about ten times as great as that of the rubber alone, and consequently for a given linear thermal current I, or linear $I^2 R$ heat loss in the wire, the $\mathcal{J}\mathfrak{R}$ drop, or temperature elevation θ, would be correspondingly increased about ten times. But at the higher temperature thus attained, the linear copper resistance R would be greater for a given electric current strength; so that in relation to electric current, the temperature elevation would be increased more than ten times by taking the wires out of the water and placing them dry in this wooden moulding.

TABLE V

TEMPERATURE ELEVATIONS AND THERMAL RESISTANCES OF WIRES IN MOULDING

	No. 16 A. W. G. $t=21.1°$ C.		No. 14 A. W. G. $t=19.1°$ C.		No. 12 A. W. G. $t=19.9°$ C.		No. 10 A. W. G. $t=19°$ C.		No. 8 A. W. G. $t=19°$ C.	
	θ Temp. Elev.	$\mathfrak{R}$ Thermal Res.	θ Temp. Elev.	$\mathfrak{R}$ Thermal Res.	θ Temp. Elev.	$\mathfrak{R}$ Thermal Res.	θ Temp. Elev.	$\mathfrak{R}$ Thermal Res.	θ Temp. Elev.	$\mathfrak{R}$ Thermal Res.
15	17.4	543.4								
20			17.6	479.9						
30	83.3	523.3	47.3	517.6	23.7	455.1	14.2	461.3		
40	173.7	437.5	93.2	498.3	51.7	507.3				
45							31.6	434.0	16.9	381.5
50			102.1	463.5	85.1	482.6				
60							61.0	427.8		
65									41.2	409.
75							106.4	417.0		
85									72.5	381.
100									105.2	363.2
	Mean	518.		490.		481.7		435.		385.
	Rubber	51.4		44.5		47.3		36.2		41.1
Braid, Air & Wood		466.6		445.5		434.4		398.8		343.9

The observed temperature elevations below 110° C. in Table V are plotted on logarithm paper in Fig. 6. The parallel straight lines there shown, fairly connecting the various series of observation points, are drawn to make an angle of 66° 25′ or the antitangent of 2.29. It has been pointed out that over a range of 100° C. the temperature elevation θ, above $t = 18°$ C., increases theoretically as $I^{2.289}$; whereas over a range of 50° C., as in Fig. 4, the temperature elevation θ increases as $I^{2.2}$. While the agreement between theory and observation is not so good in Fig. 6 as in Fig. 4, yet it may be regarded as practically satisfactory. By comparing Figs. 4 and 6, it is evident that these braided wires would carry with a given final temperature elevation some three times more current in water than in this moulding. With the braiding removed, they would carry in water nearly 3.3 times more current than when braided and in this dry wooden moulding, with the same temperature elevation. In all cases of wires cooled entirely by thermal con-

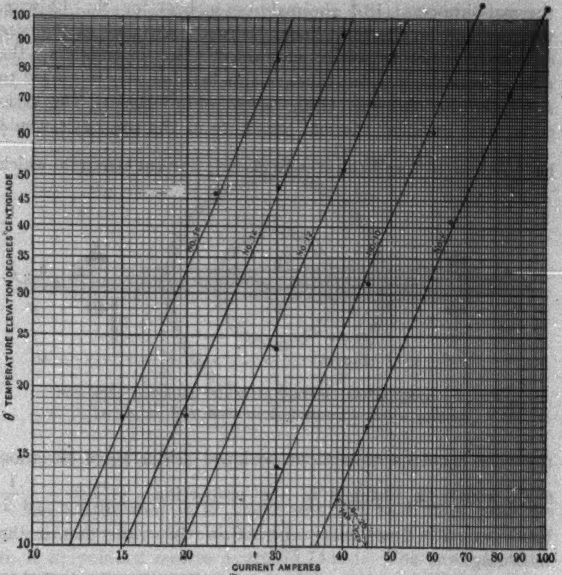

FIG. 6—Final temperature elevations of wires in moulding

duction, the electric current strength I amperes which will produce a given final temperature elevation θ, above a given initial temperature t° C., must, by formulas (11) and (12), vary as $1/\sqrt{\mathcal{R}}$, or inversely as the square root of the linear thermal resistance, assuming that the thermal resistivities in the series are substantially constant throughout their working range of temperature. Thus in Table V. the mean linear thermal resistance $\mathcal{R}$ of the rubber covering alone is shown to be 47.3 thermal-ohm-cms. (18.7 thermal-ohm-inches) for No. 12 wire, which would be the total linear thermal resistance of this size of wire in running water, unbraided. But in moulding, the mean linear thermal resistance of this braided wire increased to 481.7 thermal-ohm-cm. (190 thermal-ohm-inches). The ratio of increase in linear thermal resistance in the two cases would be $\frac{481.7}{47.3} = 10.2$ and the steady electric current strength, which the wire could carry with an assigned temperature elevation θ° C., would be changed in the proportion $\frac{1}{\sqrt{10.2}} = \frac{1}{3.2}$ times, *i.e.*, 3.2 times more current in the water than in the moulding.

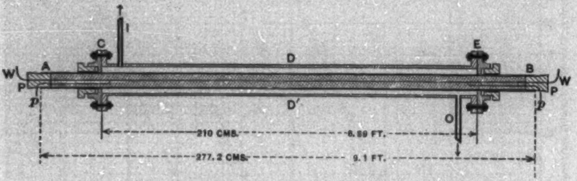

FIG. 7—Longitudinal section of water-jacketed pipe containing a test wire packed in sand, soil, or gravel

Measurements with Bare Wires Surrounded by Sand, Soil or Gravel. The heating of underground wires and cables depends, as is already known, upon the depth below the surface at which the wires are laid, and upon the thermal resistivity of the soil; as well as upon the dimensions of the wires and the currents they carry.[*] The measurement of the thermal resistivity of the soil presents some difficulty. A series of observations was made on the thermal resistivity of several varieties of sand, gravel, and plaster of paris.

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[*] "The Carrying Capacity of Electric Cables, Submerged, Buried, or Suspended in Air," by A. E. Kennelly. Minutes of the Ninth Annual Meeting, Association of Edison Illuminating Companies, 1893, p. 79. "Die Berechnung Elektrischer Leitungsnetze" Herzog-Feldmann, Vol II, p. 130.

For the above purpose, an iron pipe *A B*, Fig. 7, 277.2 cm. (9.1 ft.) long and 8.92 cm. (3.5 in.) in external diameter, was provided with a water-jacket external cast-iron pipe *C D E*, 210 cm. (6.89 ft.) long and 15.24 cm. (6 in.) inside diameter, as indicated in Fig. 8. A steady stream of tap water was allowed to flow through the water-jacket during each test, the water entering at the inlet *I* and issuing at the outlet *O*. The internal diameter of the pipe *A B* was measured both by calipers, and by finding the mass of water held by the pipe between the wooden end-plugs *P P*. This mean internal diameter was 7.77 cm. (8.06 in.).

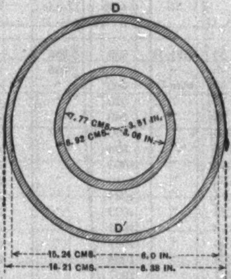

FIG. 8—Enlarged cross-section of water-jacketed pipe through *DD* Fig 7.

The copper wire *W W* under test was held at or near the axis of the tube, and smaller pressure wires *p p* were soldered to it at points 2 metres apart (78.74 in.). The mean diameter of the wire was 0.3256 cm. (0.1282 in. or No. 8 A.W.G.). Other sizes of wire were also used.

The first substance tested was a yellow sand, of moderately fine grain, obtained from a pit in a field near the Pierce Hall laboratory and may be taken as a fair sample of sandy soil. This sand was carefully dried and packed, while still warm, into the pipe *A B*, Fig. 7, around the bare wire *W W*. A steady current of water was then allowed to flow through the water-jacket for some hours, so as to bring the temperature of the apparatus substantially to 16° C., the temperature of the tap water. A strong current was then passed through the wire *W W* with the connections of Fig. 1, and steadily maintained until the resistance of this wire, between pressure taps, showed that the final temperature had been very nearly attained. Observations of resistance were obtained at frequent intervals. Table VI gives a particular series of observations obtained with a current of 128.2 amperes kept steadily flowing through the test-wire, the initial resistance balance being secured with 15 amperes. Column I gives the clock time of each observation,

TABLE VI.

OBSERVATIONS WITH 128.2 AMPERES PASSING THROUGH COPPER WIRE OF DIAM. 3.26 MM., IN DRY SAND, WATER-JACKET MAINTAINED AT 16° C.

I Time h.	m.	s.	II Time from start seconds	III Res. *r* B. A. U.	IV added to	V Resistance C side B. A. U.	VI D side B. A. U.	VII Res. of test wire Int. microhms	VIII Temp. of test wire *t*+*θ*° C.	IX Temp. rise of test wire *θ*° C.
11	30	00	0	30	grid D	850	985	4141	16.	0.°
	30	15	15	0	—	"	955	4271	24.	8.
	31	00	60	50	wire C	900	"	4522	39.4	23.4
	31	15	75	70	"	920	"	4623	45.6	29.6
	31	55	115	90	"	940	"	4723	51.7	35.7
	34	15	255	130	"	980	"	4924	64.1	48.1
	35	35	335	144	"	994	"	4995	68.4	52.4
	37	00	420	153	"	1003	"	5040	71.2	55.2
	38	40	520	160	"	1010	"	5076	73.4	57.4
	43	00	780	174	"	1024	"	5146	77.7	61.7
	46	00	960	183	"	1033	"	5191	80.4	64.4
	51	40	1360	192	"	1042	"	5236	83.2	67.2
	54	00	1440	195	"	1045	"	5251	84.1	68.1
12	01	30	1890	204	"	1054	"	5296	86.9	70.9
	5	30	2130	207	"	1057	"	5312	87.9	71.9
	12	12	2532	210	"	1060	"	5327	88.8	72.8
	22	30	3150	213	"	1063	"	5336	89.4	73.4
	27	00	3420	215	"	1065	"	5351	90.3	74.3
	36	00	3960	218	"	1068	"	5366	91.2	75.2
	46	00	4560	220	"	1070	"	5377	91.8	75.8
13	27	00	7020	220	"	1079	"	5422	94.6	78.6
	36	00	7560	229	"	1079	"	5422	94.6	78.6
	50	00	8400	229	"	1079	"	5422	94.6	78.6

column II the elapsed time from the closing of the circuit, column III the balancing resistance *r*, Fig. 1, column IV the side to which that resistance was added, columns V and VI show the respective resistances of the two galvanometer circuits, column VII gives the resistance of the 2 metres of test wire, column VIII gives the inferred temperature of the test wire, and the last column, the inferred rise of temperature.

The resistance of the standard german-silver grid *D*, Fig. 1, in the above series of measurements was 4799 int. microhms.

Fig. 9 shows at *A* the graph of the observations in the above table. The curves *B*, *C*, and *D* are the corresponding graphs of similar series of measurements with 100, 77.2 and 50 amperes respectively. These four curves show the rise of temperature in the wire during the first 7,000 seconds of steady electric current flow. About half of the final temperature elevation was reached by the wire in 150 seconds. The initial rate of temperature elevation with 128.2 amperes was about 0.5° C. per

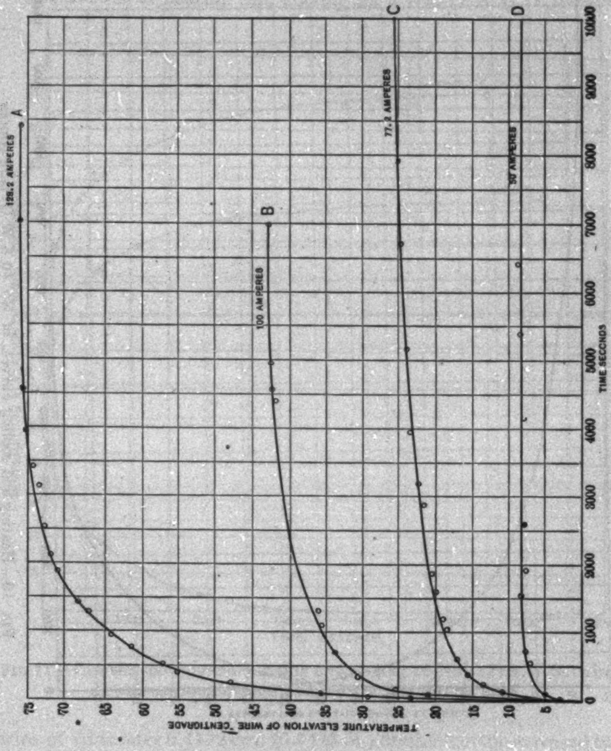

FIG. 9—Heating of wire in sand and pipe.

second. After 100 seconds, this rate fell to 0.1° C. per second, and after 1000 seconds to 0.01° C. per second.

In Fig. 10, the curves indicate the temperature elevation of another copper wire No. 10 A. W. G. (diam. 0.256 cm. or 0.1008 in.)

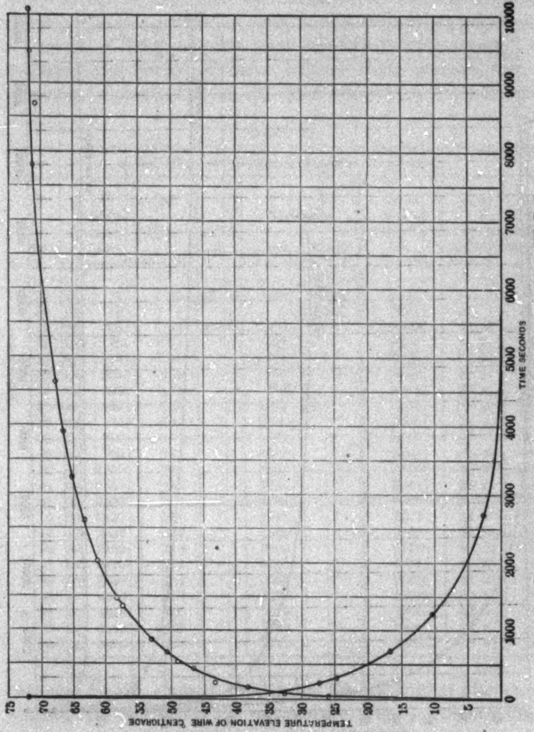

FIG. 10—Heating and cooling curves, of No. 10 A.W G. bare copper wire in dry white sand. 90 amperes.

in relation to time, after applying a steady current of 90 amperes, and also after interrupting the current. In the practically steady state, with a temperature of 6° C. in the water circulating through the water-jacket and a temperature in the wire of 78.1° C. or 72.1° C. temperature elevation, the linear thermal current was 0.3354 watts per cm. (0.852 watts per inch) and the linear thermal resistance 215 thermal-ohm-cm. (84.6 thermal-ohm-inches). By the use of formula (4), taking $d = 0.256$ cm. and $D = 7.77$ cm., the thermal resistivity of the sand was 395.9 thermal-ohm-cm.

The curves of heating and cooling for a No. 17 A.W.G. copper

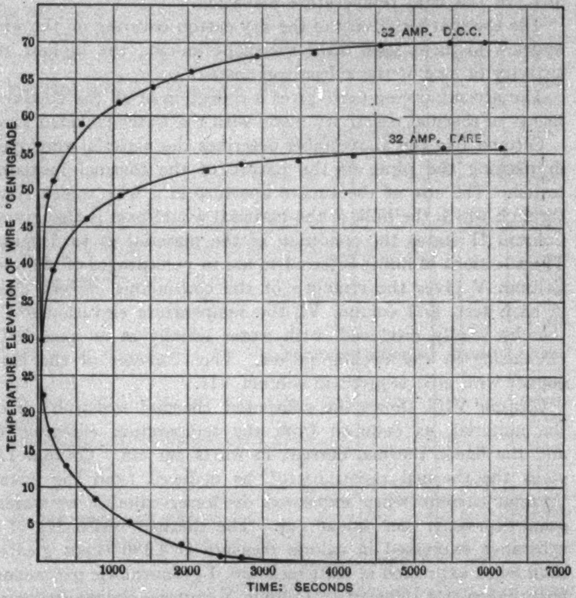

Fig. 11—Curves showing the heating and cooling of No. 17 A.W.G. wire double-cotton covered and bare in fine quartz sand.

wire of diameter 0.1132 cm. (0.0445 in.) double-cotton-covered to 0.1346 cm. (0.053 in.) are given in Fig. 11. The heating current in each case was held at 32 amperes. The upper curve shows the rise of temperature elevation with the wire when cotton-covered and packed in fine dry white quartz sand. The lower curve gives the corresponding temperature elevation rise, after the cotton covering had been removed from the wire and the same replaced in the pipe with the same quartz packing. The descending curve gives the cooling in the latter condition. It will be observed that, both in this figure and in Fig. 10, the cooling occurs more rapidly than the heating. That is, the cooling falls to 1° C. remaining temperature elevation in about half the time that the heating process requires to attain within 1° C. of the final temperature elevation.

The thermal resistivity of the dry cotton covering on the wire appears to have been 2373 thermal-ohm-cm., the highest resistivity of any of the substances tested.

The accompanying table gives a collection of all the measurements of thermal resistivity made with the water-jacketed pipe.

Column I in the above table describes the material employed in packing the pipe, or the nature of the thermal insulator tested. The size of the square aperture in a wire screen sieve through which the bulk of the material would pass is also given. Column II states the condition of the material as to dryness. The additions of liquid referred to are in percentages of volume. Column V gives the strength of the continuous current used in each test, and column VI, the temperature elevation θ° C., thereby finally produced, with water usually at or near 5° C. circulating in the cooling jacket. The diameter of the bare copper wire used is given in column VII.

Column VIII shows the computed thermal resistivity σ of the material, as deduced from the temperature elevation θ, and the linear thermal current in watts per cm. Column IX gives the thermal resistivity σ', as deduced from the linear thermal current when expressed in lesser calories, or water-gram-deg.-cent. per linear cm. The thermal resistivity of a substance expressed in calorie measure is 4.186 times greater than when expressed in watt measure, 1 gram-calorie per second being taken as 4.186 watts. Column X contains the thermal conductivity of the substances in watt measure, or the reciprocal of σ in column VIII. Column XI contains the thermal conductivity of the substances in caloric measure, or the reciprocal of σ' in column IX.

It will be observed that the thermal resistivity varied between 161.4 thermal-ohm-cm. for quartz sand with 20% water and 761.7 thermal-ohm-cm. for dry powdered plaster of paris. The dry cotton covering of the wire whose heating is shown in Fig. 11, had, however, a resistivity of 2373 thermal-ohm-cm.,

TABLE V

THERMAL RESISTIVITIES OF MATERIALS

I Material	II Condition	III % of Air Space Dry.	IV Sp. G. Dry.
Yellow sandy soil containing quartz, mica, loam and other materials. Average mesh 0.4 mm. x 0.4 mm.	Dry	35.[illegible]	1.63 or corrected for air 2.54
Fine white quartz sand obtained from N. Y. State	Dry	43.2	1.46
	"	43.2	1.46
	20% water	23.0	corrected 2.57
	"	"	
	10 " %	33.4	
Average mesh 0.25 mm. x 0.25 mm.	"	"	
	"	"	
	"	"	
	"	"	
	10% kerosene	33.3	
	"	"	
		"	
	Dry	43.2	1.46
Crushed quartz, mesh 0.85 mm.	Dry	47.6	1.33
Same crushed to mesh 0.42 mm.	Dry	33.7	1.50
Fine gravel containing sand mesh, 0.5 mm.	Dry	31.8	1.60
	5% water.	26.8	
Fine sandy soil.	Dry	42.7	
	20% water	22.7	
Powdered plaster of Paris.	Dry		

LE VII

S TESTED IN WATER-JACKETED PIPE

V Testing Current amp.	VI Temp. Elevation θ °C.	VII Diam. of Test Wire, mm.	VIII Thermal Resistivity ohm-cm. watt measure σ	IX Thermal Resistivity calorie measure σ′	X Thermal Conductivity watt measure k	XI Thermal Conductivity calorie measure k′
128.2	78.6	3.256	349.6			
100.	42.9	"	352.4			
77.2	26.	"	385.2			
50.	8.4	"	312.4			
80.	87.5	2.053	350.8			
75.	77.4	"	367.9			
60.	42.8	"	352.5			
40.	16.6	"	341.4			
		Mean	351.5	1471.	0.002845	6.798x10-4
90.	78.1	2.56	395.9			
70.5	38.5	"	386.7			
		Mean	391.3	1638.	0.002556	6.105x10-4
90.	26.7	2.56	173.4			
70.	13.2	"	149.3			
		Mean	161.4	675.6	0.006196	14.8 x10-4
100.	46.4	2.56	229.3			
90.	38.0	"	237.8			
80.	28.0	"	230.7			
70.	20.6	"	227.1			
60.	14.3	"	221.3			
		Mean	229.2	959.4	0.004363	10.42x10-4
100.	63.9	2.56	298.1			
80.	36.4	"	291.4			
60.	19.0	"	287.8			
		Mean	292.4	1224.	0.003420	8.17 x10-4
22.	55.8	1.132	402.2	1684.	0.002486	5.938x10-4
100.	62.1	2.56	292.0			
75.	32.5	"	300.8			
		Mean	296.4	1241.	0.003374	8.058x10-4
100.	55.2	2.56	265.2			
75.	28.7	"	269.4			
		Mean	267.3	1119.	0.003741	8.937x10-4
75.	33.0	2.56	345.0	1444.	0.002899	6.925x10-4
100.	58.1	"	273.1			
75.	28.5	"	264.2			
		Mean	268.6	1124.	0.003723	8.897x10-4
75.	58.8	2.56	490.4	2053.	0.002039	4.871x10-4
75.	40.2	"	355.9	1490.	0.002810	6.711x10-4
75.	106.3	2.56	761.7	3188.	0.001313	3.137x10-4

which corresponds to a thermal conductivity of 4.214×10^{-4} thermal-mhos-per-cm. in watt measure, or 1.007×10^{-4} thermal-mhos-per-cm. in gram-calorie measure. This agrees with the value for cotton wool given by Peclet.[9]

Fig. 12 shows the relation of the observations with the temperature elevation of wires in the water-jacketed pipe to the steady current strength when plotted on logarithmic paper. The parallel straight lines are drawn to make an angle of 66° 30′ or the anti-tangent of 2.3, to cover a range of 100° C. temperature elevation from an initial temperature of 6° C., in accordance with formula (15) adapted to 100° C. instead of 50° C. The agreement between the observation points and these straight lines of average exponent 2.3 is fairly satisfactory from an engineering standpoint.

The following conclusions may be drawn from the observations here reported:

(1) The fundamental formula for the direct-current final heating of a wire that cools by conduction is (12)

$$\frac{\theta}{1+a\,\theta} = K\,I^2$$

where K is a constant for the wire determined by the total linear thermal resistance. This formula applies to concealed wires, *i.e.*, to insulated wires in water, in the ground, or in wooden moulding.

(2) The thermal resistivities of the various substances tested with different temperature elevations, including rubber composition, braiding, moulding, and various soils, may, for practical purposes, be regarded as constant, *i.e.*, not appreciably affected by temperatures up to 100° C.

(3) Wet braiding on a No. 14 rubber-covered wire added a linear thermal resistance of 8.7 thermal-ohm-cm. (2.46 thermal-ohm-inches) and raised the final temperature of the wire immersed in water by about 2° C. with 50 amperes.

(4) The linear thermal resistance of the rubber-covered wires in dry wooden moulding was about 10 times greater than when immersed in water, thus increasing their temperature elevations more than 10 times with a given current or reducing their current-carrying capacity more than 3 times for a given temperature elevation.

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[9] "C. G. S. System of Units," by Everett—Heat Conduction of Woolly Substances, p. 128. London, 1891.

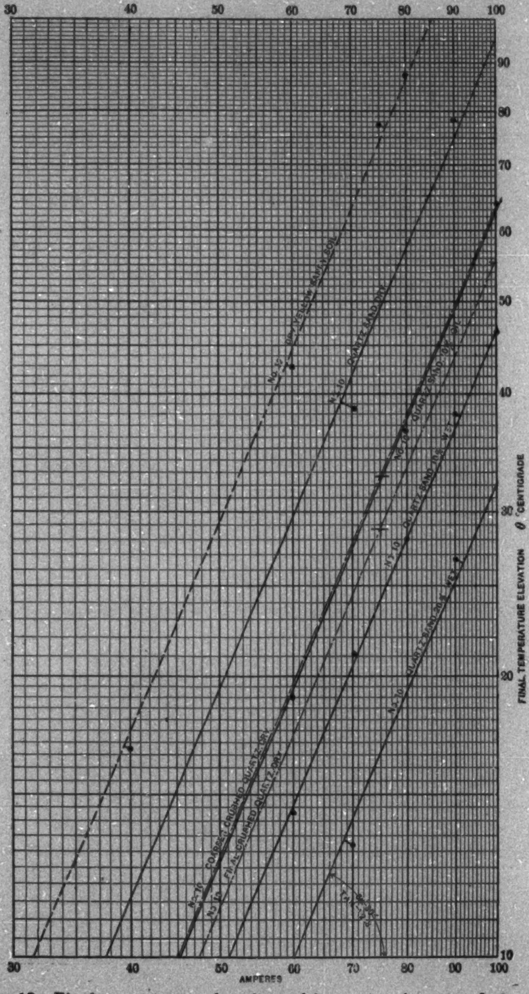

FIG 12—Final temperature elevations of bare wires in water-jacketed pipe, with different packings.

(5) When plotted on logarithm paper, the final temperature elevation of a wire in relation to steady current strength is nearly a straight line of inclination $\tan^{-1} 2.2$ (Fig. 4) for temperature elevations not exceeding 50° C., and not far from a straight line of inclination $\tan^{-1} 2.3$ for temperature elevations not exceeding 100° C. (Figs. 6 and 12).

(6) A No. 12 A.W.G. copper wire, rubber-covered, and immersed in water substantially attained its final temperature elevation in 300 seconds, or 5 minutes, after applying a steady current. The same wire in dry wooden moulding took 1800 seconds, or 30 minutes, and the same wire, bared but packed in sand within a water-jacketed pipe of 7.77 cm. (3.06 in.) internal diameter, took about 7800 seconds, or 130 minutes, to reach a similar approximation to final temperature elevation.

(7) The wires in the water-jacketed pipe cooled more quickly than they heated.

(8) Changing the size of the wire in the water-jacketed pipe from No. 8 (0.326 cm.) to No. 12 (0.205 cm.) did not appreciably affect the thermal resistivity of sandy soil as measured with these wires (351 thermal-ohm-cm.) Similarly, changing the size from No. 10 (0.256 cm.) to No. 17 (0.113 cm.) did not appreciably affect the thermal resistivity of dry quartz sand as measured by those wires (400 thermal-ohm-cm.).

(9) The thermal resistivity of the sandy soils tested was greatest when those soils were dry, and diminished with the addition of water or oil to them.

(10) The thermal resistivity of a sample of crushed quartz was greater with the material in a coarse condition. Crushing the particles of quartz to about half their previous linear dimensions reduced the thermal resistivity of the material about 10%.

(11) The lowest thermal resistivity observed was that of quartz sand with 20% of water added by volume (161.4 thermal-ohm-cms) the highest was that of the white dry double cotton covering of a wire (2373 thermal-ohm-cm.), both in watt measure.

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A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

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POWER-FACTOR, ALTERNATING-CURRENT INDUCTIVE CAPACITY, CHEMICAL, AND OTHER TESTS OF RUBBER-COVERED WIRES OF DIFFERENT MANUFACTURERS

BY HENRY W. FISHER

Probably no form of insulating material for wires has been so frequently discussed as india rubber and its component ingredients, known commercially as "rubber." Very many tests have been devised to determine the percentage of rubber and other materials, and especially the amount of fine para.

In a compound containing both pure para and other grades of rubber, it will probably never be possible to tell the relative percentages of each. If the amount of inferior grades of rubber is considerable, an indication of the fact can be obtained from some of the various tests now used.

Specifications have been devised with a view to securing, by the application of certain well defined tests, an absolutely certain percentage of pure para. In some of these cases, the manufacturer could have furnished a better compound containing wax or similar solid hydrocarbons mixed with the dry mineral filler, but the presence of such materials would make it impossible to tell how much of the rubber was fine para.

In view of these rather complicated conditions, several of the manufacturers of rubber-covered wire framed a set of specifications which would ensure 30% para and give at the same time latitude to the manufacturer to use such other ingredients as in his experience would make a compound having toughness, elasticity, resistance against high voltages, and other desirable qualities. These specifications were brought to the attention of the Institute in a paper by Mr. Wallace Clark, read in New York on April 27, 1906.

The object of the present paper is to give the results of certain tests which, while not strictly new, have not been applied commercially to rubber-covered wires. One reason for conducting this investigation was to see if power-factor tests would not live an insight into the qualities of different makes of rubber-insulated wire.

The definition of power-factor, as here used, is the ratio of the power absorbed in the rubber compound to the apparent loss as found by multiplying the charging current by the applied volts. Practically speaking, it may be considered as an indicator of the loss in the dielectric around the wire and therefore a low power-factor is desirable.

A considerable amount of work has been done by various experimenters to determine how the losses in condensers and cables vary with the applied volts, frequency, capacity, etc. One of the most recent investigations of this sort was given in the paper of Dr. Paul Humann which appeared in the " Elektrische Bahnen U. Betriebe" from August 24 to September 24, 1906.

Dr. Humann's formula for the loss in the dielectric of paper-insulated cables is as follows:

$$W = K E^2 n C \tag{1}$$

Where W = the loss in watts,

K = a constant varying with different insulating compounds,

E = the effective pressure in volts,

n = the frequency of the alternating current,

C = the inductive capacity of the cable.

The proof of the above formula is as follows:

$$\text{power-factor} = p.f. = \frac{W}{I\,E} \tag{2}$$

$$I = \text{the charging current} = \frac{2\pi\, n\, C\, E}{10^6} \tag{3}$$

Substituting and transposing,

$$W = \frac{(p.f.)\,2\pi}{10^6} E^2 n C = K E^2 n C \tag{4}$$

where $K = \frac{(p.f.)\ 2\pi}{10^6}$. The loss is in watts and it varies in direct proportion to the frequency, capacity and power-factor and to the square of the electromotive force.

The methods adapted by Dr. Humann were somewhat involved and complicated, but nevertheless ingenious. In order to get true readings he had to expurgate the harmonics of the alternating-current voltage, producing thereby a true sine-wave electromotive force.

The writer is much indebted to Dr. Rosa, of the Bureau of Standards, for outlining some extremely simple methods to determine power-factors, capacities, inductances, etc. This led to the design of a special form of bridge having non-inductive resistances with minimum inductive capacities, and suitable binding-posts for the various apparatus employed. The rest of the outfit consisted of a vibration galvanometer, and a motor-generator the speed of which was kept absolutely constant by an electrically driven tuning-fork. The rate of vibration of the tuning-fork could be varied by the application of weights near the end of the forks.

By careful adjustment of both the tuning-fork and galvanometer they could be brought into synchronism, when the latter becomes a most sensitive instrument for indicating minute alternating currents. Moreover, as the galvanometer needle responds only to the fundamental period of the alternating-current circuit, and is not at all affected by existing harmonics, it is unnecessary to employ a sine-wave electromotive force for measurements of capacity, inductance, and power-factor.

The method employed in these researches is based on the fact that a cable or condenser, the absorption and leakage of which is not zero, is equivalent to a cable or condenser with zero absorption in series with a resistance, called the "equivalent resistance," such that the angle of lead between the electromotive force and current shall be $90°-\theta$.

With a perfect condenser $\theta = o$. The power-factor $= \cos (90-\theta) = \sin \theta$. (5)

Fig. 1 shows the diagram of the connections and arrangement of the various instruments.

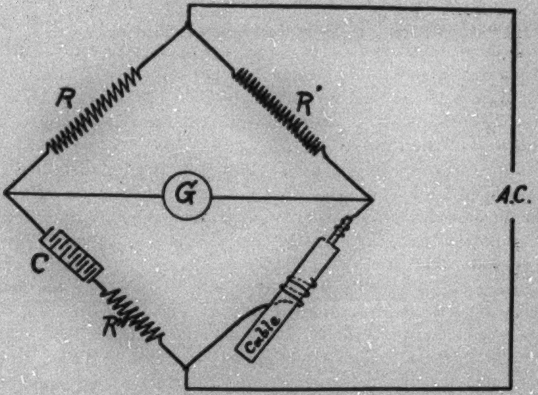
R and R' are the ratio arms of the bridge; R'' is the resistance which is placed in series with the standard condenser C; $A.\ C.$ is the alternating-current source; and G is the vibration galvanometer. The plan of procedure is first to vary R or R' until a partial balance is obtained, then adjust R'' and R until the galvanometer mirror ceases to vibrate, when the power-factor of the cable =

$$\text{Power-factor of condenser} + \frac{2\pi n R'' C}{10^6} \qquad (6)$$

and capacity of cable $= \frac{R}{R'} \times C$

Where n = the cycles per second and C = the capacity of the standard condenser.

FIG. 1.



The reflection from the galvanometer mirror of a lamp filament was used until a balance was practically obtained, then the reflection of a scale was observed, and the resistances varied until the scale divisions were sharp and well-defined.

This method is so extremely sensitive that in making tests of cables it was generally impossible to adjust the bridge for any length of time so that the galvanometer mirror did not vibrate. There is apt to be a continual slight variation in capacity and power-factor. With perfect standard condensers, capacities can be compared to within one point in 5000.

Owing to some peculiar factory vibration which affected the vibration galvanometer, it was impossible to make the tests at a frequency of 60 cycles per second as originally intended, and

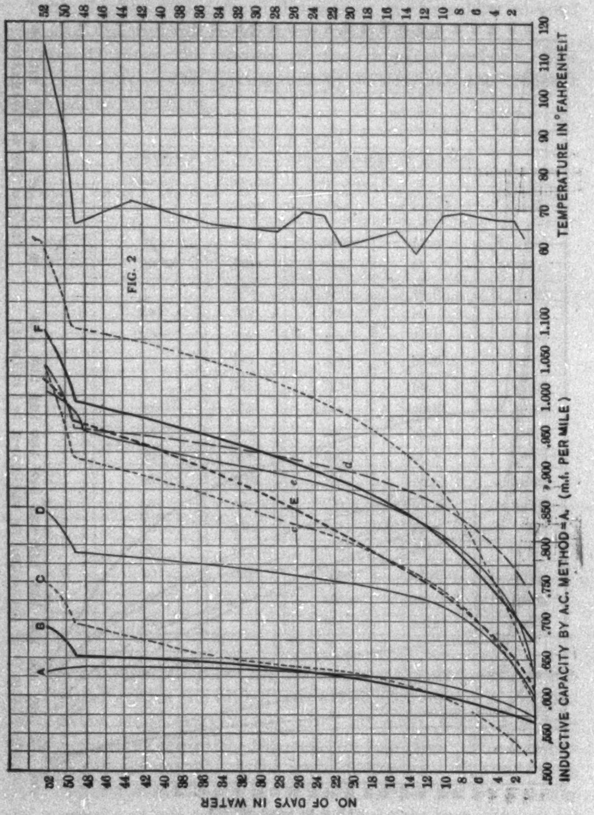


FIG. 2

hence after considerable adjustment a frequency of 53.5 cycles was employed throughout the tests.

Coils of rubber-covered wire of various manufacturers were purchased in different cities. These were cut into lengths of 210 ft. and placed in a metallic tank which was afterwards filled with a strong saline solution. Each curve represents therefore the results of tests on two or more coils of wire.

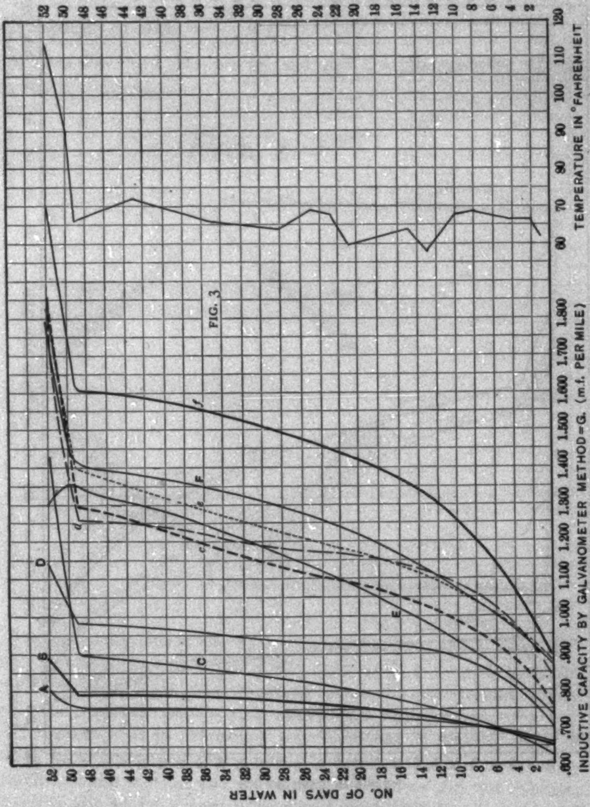


FIG. 3

The voltage tests were made on four samples of each original coil. The samples were four feet long, three feet of which was under water for 24 hours before the test was applied. Samples of each coil were reserved for chemical analysis, but owing to the time required for this work returns were not received from all coils. Sufficient tests were made, however, to permit of a general comparison between most of the samples.

Table I gives the general dimensions of the rubber-covered wire and the average break-down voltage tests.

Table II gives the results of the chemical analysis. The different samples are represented by letters, and the different materials by numbers.

TABLE NO. I.

DIMENSIONS AND BREAK-DOWN VOLTAGES OF SAMPLES.

Sample Letter	Size of Wire B. and S. G.	Diameter in mils over		Thickness of Rubber	Break-down Voltage
		Braid	Rubber		
A	10	323	209	53.5	22860
B	10	280	204	51	23100
C	10	293	209	53.5	15960
c	10	302	202	50	14450
D	10	303	213	55.5	16750
d	10	292	205	51.5	16300
E	10	285	194.5	46	13600
e	10	303	201	49.5	16770
F	10	300	209	53.5	22040
f	10	306	209	53.5	15120
G	10	245	195	46.5	23600
H	10	249.5	193.5	45.75	18355
h	10	246	197	47.5	12825
I	10	252.5	199	48.5	17775
i	10	257	201	49.5	18650
J	12		235	77	23035
K	12		234	76.5	22500

Chemical tests of rubber are difficult to make, and owing to the fact that several of the ingredients are slightly soluble in solvents other than those particularly used for each, there is a possibility of slight errors in the amount reported. No. 2 is the acetone extract and No. 3 the pyridine extract. The tests were most carefully made each in the same manner and by a person the accuracy of whose analysis had previously been checked by his reports of samples having known ingredients.

In designating the wire of any one manufacturer the large character represents the higher priced wire and the small character

TABLE II

SPECIFIC GRAVITY AND COMPOSITION OF RUBBER

Material Number.	Name of Material	Sample Letter and % of Material																
		A	B	C	*c*	D	*d*	E	*e*	F	*f*	G	H	*h*	I	*i*	J	K
	Specific Gravity.........	1.75		1.76	1.86	1.86	1.97	1.66	1.81	1.91	2.02	1.75	1.79		1.74	1.77		
1	Rubber (H_{16} C_{18}).......	26.84		23.32	22.42	20.64	15.52	16.67	16.72	20.12	17.20	27.32	21.85		23.33	22.43	28.30	27.96
2	Free oils, Resins, Waxes Solid Hydro-carbons.....	4.71		9.92	9.75	5.80	7.17	17.99	10.90	4.69	3.61	3.49	6.10		7.04	7.45	3.70	2.99
3	Pitch, Tar, Bituminous Substances...	2.16		1.54	1.29	2.86	2.90	3.41	3.59	1.80	2.62	1.79	2.22		2.98	1.99	0.375	0.375
4	Ether Extract...........	0.300		0.915	0.97	1.22	0.64	0.34	0.27	0.35	0.47	0.51	0.35		0.50	0.73	0.55	0.28
5	Blown oils Fatty Matters...........	0.81		0.66	1.02	1.15	1.85	2.02	0.83	0.90	0.44	0.18	0.60		0.18	0.74	0.32	0.00
6	Combined Sulphur.......	2.41		3.41	5.08	3.83	4.26	5.47	3.48	4.45	3.01	3.01	3.37		3.64	3.65	2.50	2.62
7	Free Sulphur............	0.23		0.56	0.46	0.20	0.20	0.44	0.71	0.20	0.27	0.24	0.32		0.25	0.25	0.32	0.40
8	Organic Matter.......... (soluble in water)	0.38		0.67	0.97	0.43	0.67	0.90	0.78	0.68	0.64	0.43	0.78		0.66	0.75	—	—
9	Moisture.................	0.14		0.24	0.46	0.30	0.210	0.25	0.57	0.21	0.15	0.34	0.34		0.20	0.43	0.41	0.310
10	Mineral Matter..........	62.03		58.77	57.58	63.60	66.61	52.53	62.16	66.62	71.61	62.71	64.08		61.22	61.60	63.53	65.38

of the same letter the lower priced wire of the same manufacturer.

The measurements made, which are represented by curves, were as follows.

A, the inductive capacity by alternating-current method;

G, the inductive capacity by the ballistic-galvanometer method;

The insulation resistance after one minute's electrification, by direct deflection method;

P. F., the power-factor;

W, the total loss at a frequency of 53.5 cycles and electromotive force = 75 volts.

For convenience in comparison the loss *W* is multiplied by 50, making it equal to that of 50 miles of wire, when the lowest loss is about one watt.

Owing to the time required to complete these tests, it was necessary to make two sets of measurements on two different lots of wires and hence the reason for two sets of curves. On account of the great variation in insulation resistances, two sheets with different scales had to be used. These are given in Fig. 4 and 5, and to get a relative comparison between the two sets of curves the insulation resistance of wire *e* is shown in both figures.

On the right-hand side of each set of curves is given the variation of temperature with time. It was impracticable to keep the temperature at the same point throughout the tests, but the variation in temperature would make little difference in all the various tests, except possibly those of insulation resistance. As the variation of temperature was alike with all coils, the relative average results may be considered sufficiently correct for the purposes of this paper, which deals with comparisons rather than with absolute values. The last two tests were taken at temperatures of about 90° and 115° fahr., thus affording a chance of comparing the various temperature coefficients.

Some explanation of the curves represented by the term *A/G* is here necessary. This is the ratio of the inductive capacity measured by the alternating-current method to that measured by the usual galvanometer method. In a paper by the writer, read two years ago at the Asheville convention, the statement was made that the dielectric loss in a cable seems to increase as the above ratio becomes smaller. This appears to be generally true here, too.

Inductive capacities are usually measured by the ballistic galvanometer method and A/G is the factor by which said capacities must be multiplied in order to get the true alternating current capacity.

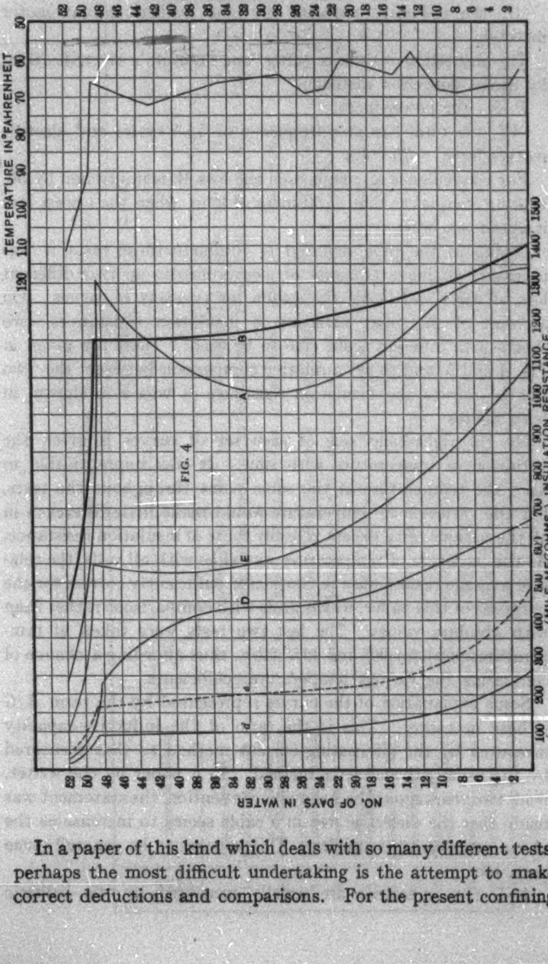


FIG. 4

In a paper of this kind which deals with so many different tests, perhaps the most difficult undertaking is the attempt to make correct deductions and comparisons. For the present confining our remarks to Fig. 2 to 8 inclusive, it is at once noticeable that the insulation resistance, power factor, and A/G decrease with the time of immersion in water, and the others increase

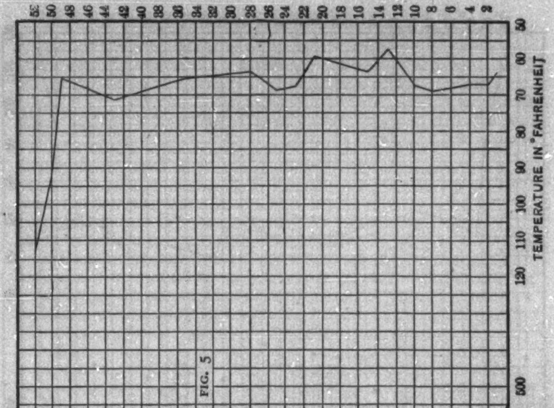


FIG. 5

with the time of immersion. This is what one would naturally expect, because all the samples were braided and therefore the water would take some time to fill all the interstices around the rubber.

It is also evident that the rate of change is generally less where the percentage of rubber is high, as with samples *A*, *B*, *C*, and *D*. *B* was not analyzed, but it evidently contained a large percentage of rubber.

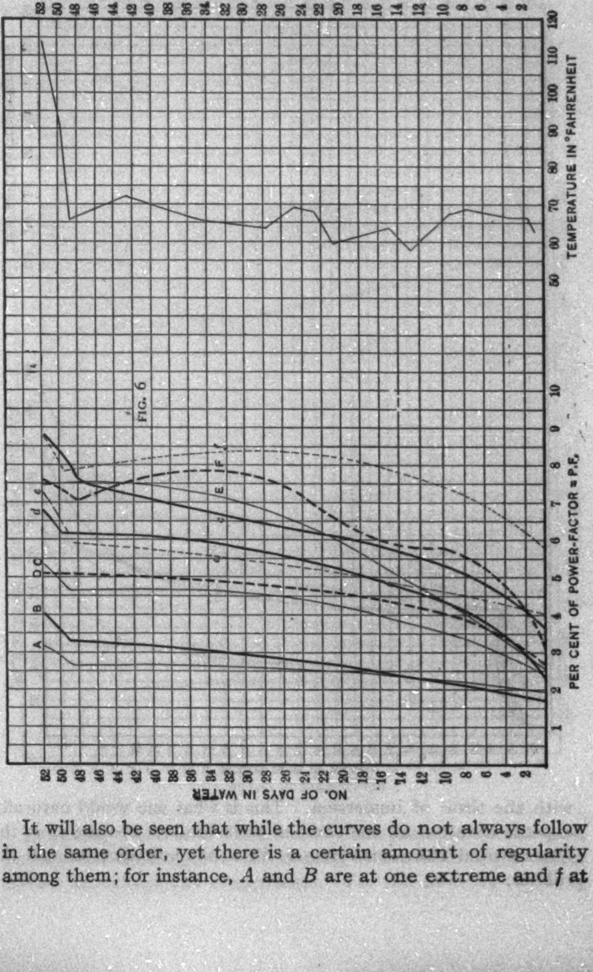


FIG. 6

It will also be seen that while the curves do not always follow in the same order, yet there is a certain amount of regularity among them; for instance, *A* and *B* are at one extreme and *f* at the other. The general tendency is for the insulation resistance to vary inversely as the capacity. There are, however, some notable exceptions which will be considered in due time.

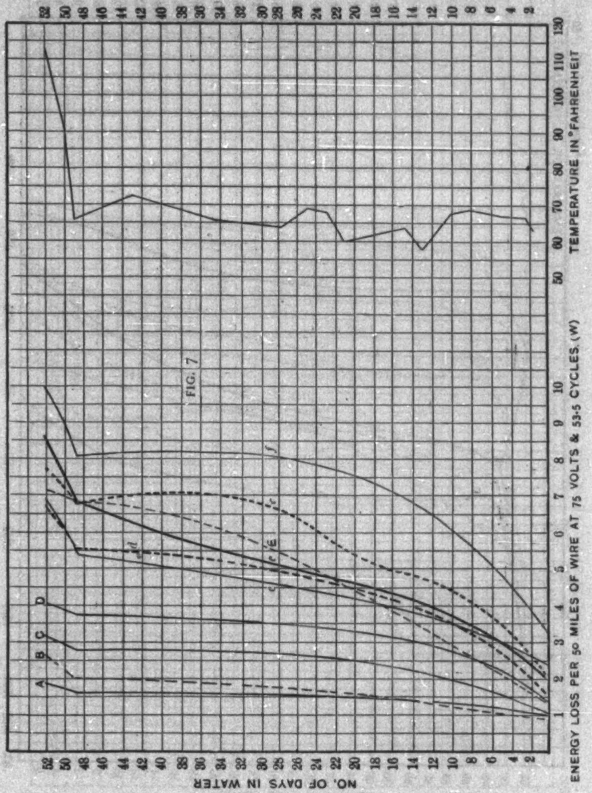


FIG. 7

We may here ask the pertinent question; what are the desirable qualities of a rubber insulating compound? This might be answered as follows: 1, good materials and uniformity of structure; 2, great electrical strength; 3, good lasting properties. Insulation and capacity tests give us some idea of the first, high-voltage tests of the second, and while long-time tests are essential for the third, yet power-factor or loss-tests

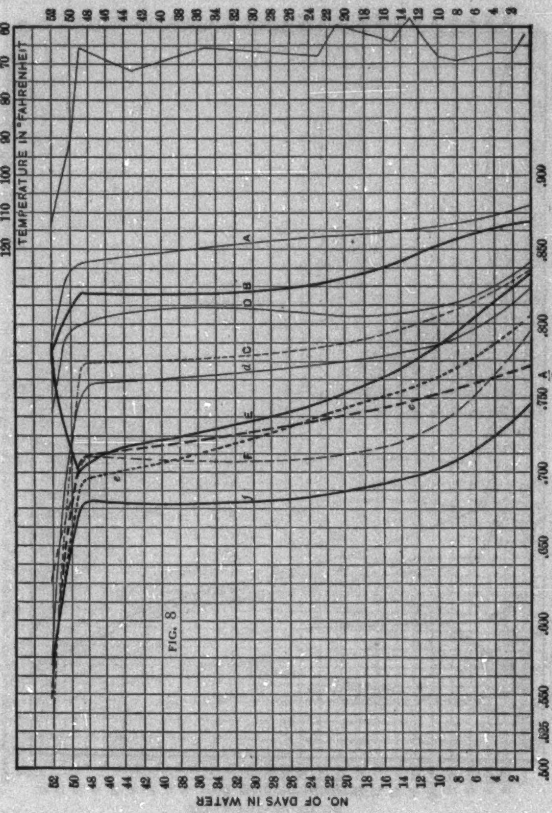


FIG. 8

covering a shorter period of time may indicate any tendency to gradual disintegration.

Now, making some general comparisons, we find that *A* and *B* have high insulation resistance, high resistance to voltage, small

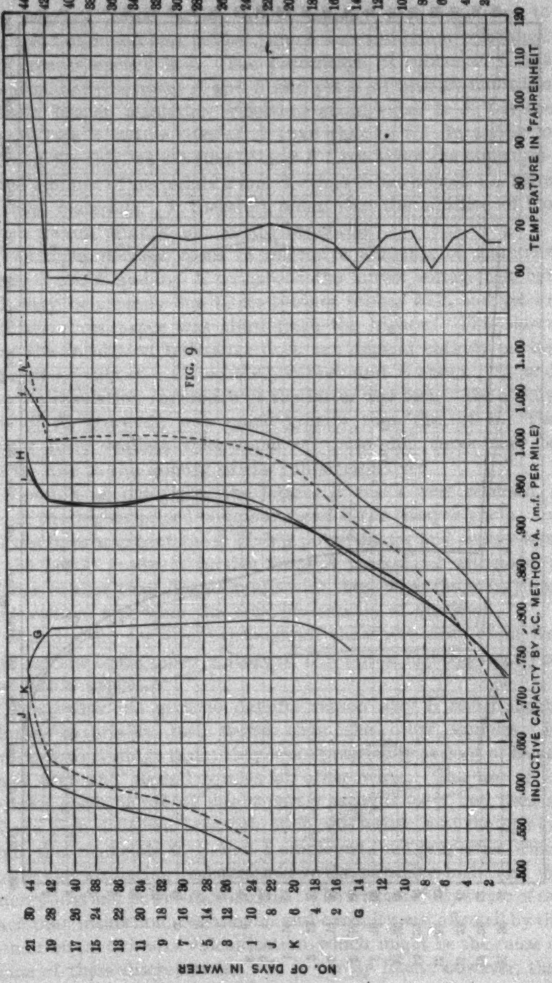

TEMPERATURE IN °FAHRENHEIT
60
70
80
90
100
110
120
INDUCTIVE CAPACITY BY A.C. METHOD - A. (m.f. PER MILE)
.500
.550
.600
.650
.700
.750
.800
.850
.900
.950
1.000
1.050
1.100
G
H
I
J
K
L
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 G
21 19 17 15 13 11 9 7 5 3 1 J K
NO. OF DAYS IN WATER

FIG. 9

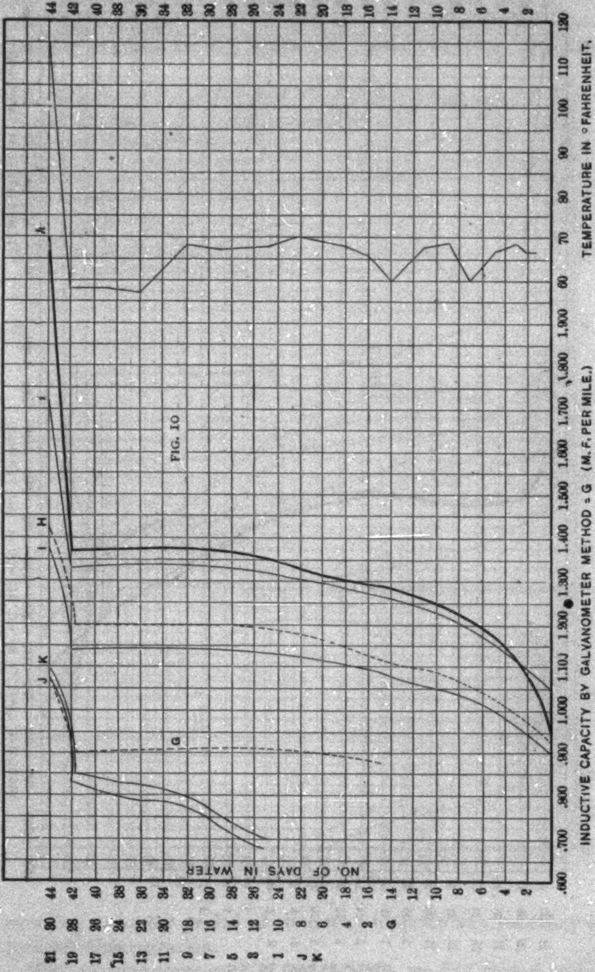


FIG. 10

TEMPERATURE IN °FAHRENHEIT.
INDUCTIVE CAPACITY BY GALVANOMETER METHOD = G (M.F. PER MILE.)
NO. OF DAYS IN WATER
A
I
H
I
J
K
G
.600
.700
.800
.900
1.000
1.100
1.200
1.300
1.400
1.500
1.600
1.700
1.800
1.900
60
70
80
90
100
110
120
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
G
21
19
17
15
13
11
9
7
5
3
1
J
K

energy loss, and *A* shows a higher percentage of rubber. *F*, on the contrary, while having about equally good resistance to voltage, has much less rubber, much less insulation resistance, and greater energy loss. The percentage of rubber in *C* lies about midway between *A* and *F* and yet *C* withstands much less voltage, has an insulation resistance about equal to *F*, but the energy loss is nearer that of *A* than that of *F*. In trying to account for this, we see that *A* and *F* have about the same combined amount of materials 2 and 3, while *C* has almost 4% more of those materials. It therefore seems that the addition of too much waxes, pitches, etc. is not beneficial.

The most notable cases of excessive amounts of materials 2 and 3 are *E* and *e*. *E* withstood the lowest voltage test but this may be entirely due to its thinner rubber wall, and yet its insulation resistance was third from the highest. This shows that the insulation resistance does not depend entirely on the amount of rubber. *C* had 23% rubber and *E* about 17%, and yet the insulation resistance of the latter was best. The energy loss of *E*, however, was much greater than that of *C*. The writer fully realizes that some of these differences may be partly due to the quality of the rubber employed.

Through an oversight, the letters *E* and *e* were reversed, *e* being the higher priced compound and *E* the cheaper grade. In all the figures except those giving power-factor and energy loss, *e*, the better grade, is further from *A* than *E*.; *e* withstood a higher voltage than *E*, and hence with these wires the energy test and voltage test were the true indications of quality.

D and *d* are consistent throughout the whole series of curves, and yet the break-down voltage of *D* is not as high apparently as one would expect.

The writer can give no definite reason why *F* and *f* should almost invariably test worse than the other samples. In break-down voltage tests, they were practically as good or better than first and second grades of other wires. The use of an inferior grade of rubber might partly account for it, but, because of the high dielectric strength of *F*, the writer is of the opinion that the materials 2, 3, and 5 employed, had properties which made the insulation resistance low, the capacity high, and the energy-loss and power-factor high. The writer is fully aware of the fact that insulation, resistance, and capacity are affected by the conditions and time of vulcanization, which might be the cause of some of these discrepancies. It is hardly likely, however, that

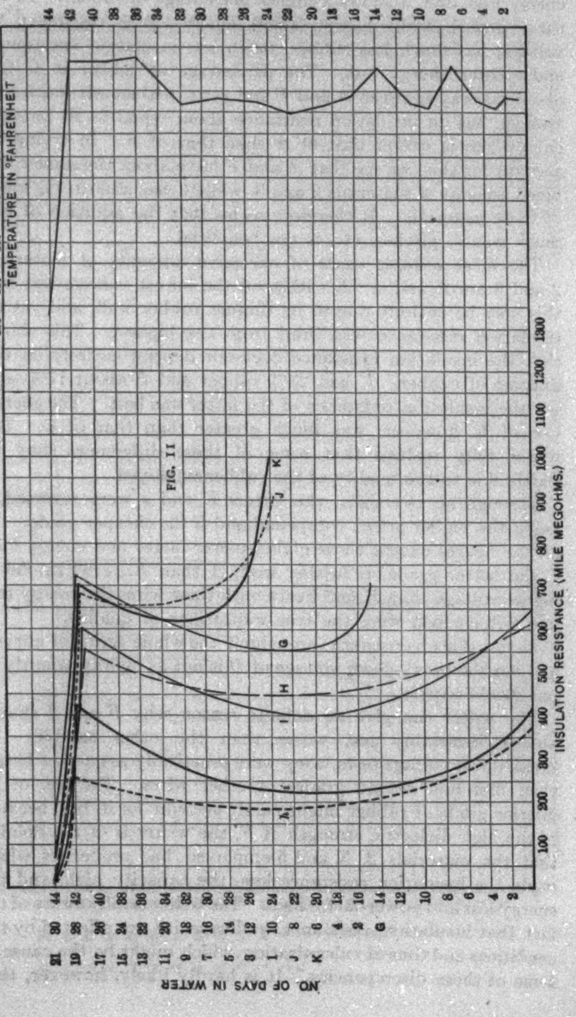

TEMPERATURE IN °FAHRENHEIT
50
60
70
80
90
100
110
120
INSULATION RESISTANCE (MILE MEGOHMS.)
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
G
21
19
17
15
13
11
9
7
5
3
1
J
K
NO. OF DAYS IN WATER
G
H
I
J
K
J
K

FIG. II

F and *f* were vulcanized at the same time, and hence the theory of slightly defective material is probably the nearest correct.

It is interesting to note the peculiar change of insulation resistance of sample *A*. There was first a gradual decrease and then an increase to the time when heat was applied, when the insulation again became less. After rubber covered wire is vulcanized, there seems to be a tendency for the insulation resistance to increase and the capacity to decrease. This probably accounts for the above effect. There are other samples which show this tendency to improvement after the lapse of time, but in a less marked degree.

Referring once more to the break-down voltages, it is well to bear in mind the fact that long coils of wire will not withstand anything like the break-down voltages which punctured the four-foot samples. In a few cases, some of the four-foot samples broke down at a much lower voltage than the average of the others made by the same manufacturer.

The second lot of samples are designated as follows: *G*, *H*, *h*, *I*, *i*, *J* and *K*. The curves representing tests made on these are found in Figs. 9, 10, 11, 12, 13, and 14.

Samples *H*, *h*, and *I*, *i* were tested for 14 days when two samples, the average of which is given by the *G* curves, were put in the same tank. At the end of 23 days, the samples *K*, *L* were put in the tank. There are, therefore, three sets of time figures, but under two of these are placed the letters of the samples to which they refer, and the third set must be used for *H*, *h*, *I*, *i*.

The sample *G* seems, from the chemical analysis, to be reasonably close to 30% rubber. The thickness of rubber is the smallest, and yet the break-down voltage was the largest.

All the curves of *G* show but a slight tendency to variation after the lapse of a few days, and there is a general indication of a gradual improvement with time.

The insulation resistance of *G* is not so high as that of *A* and *B*. This difference is partly accounted for by the difference in the rubber wall, and partly by the amounts and kind of materials 2 and 3. The power-factor and the energy-loss of *G* are also greater than those of *A* and *B*, but this is probably partly due to the smaller amount of materials 2 and 3. (See remarks later on about *J* and *K*.)

All the insulation resistances given in Fig. 11 become better near the end of the tests, this is partly due to a drop in temperature which occurred for the two tests prior to increasing the

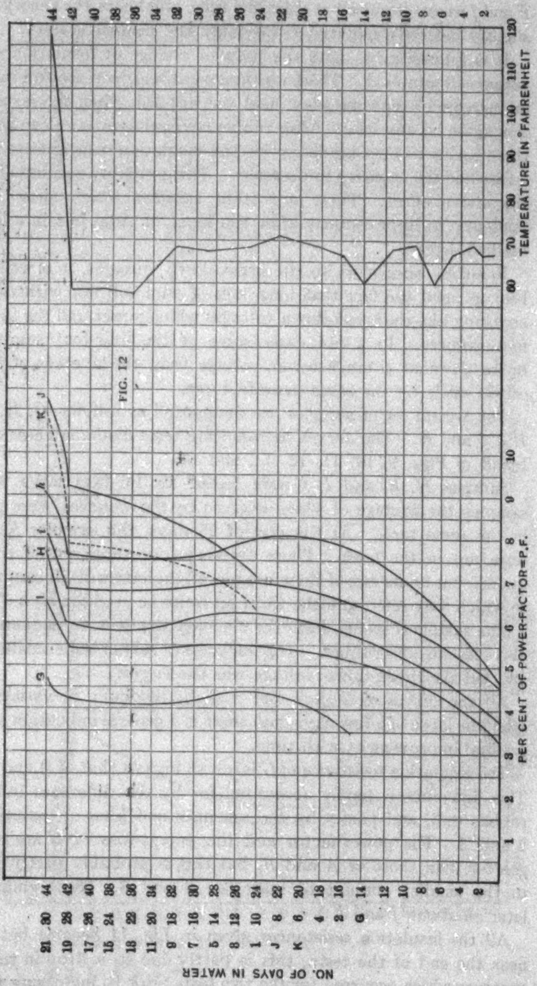

TEMPERATURE IN °FAHRENHEIT
120
110
100
90
80
70
60
PER CENT OF POWER-FACTOR=P.F.
10
9
8
7
6
5
4
3
2
1
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
21 19 17 15 13 11 9 7 5 3 1 J K
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 G
NO. OF DAYS IN WATER
J
K
h
t
H
I
G

FIG. 12

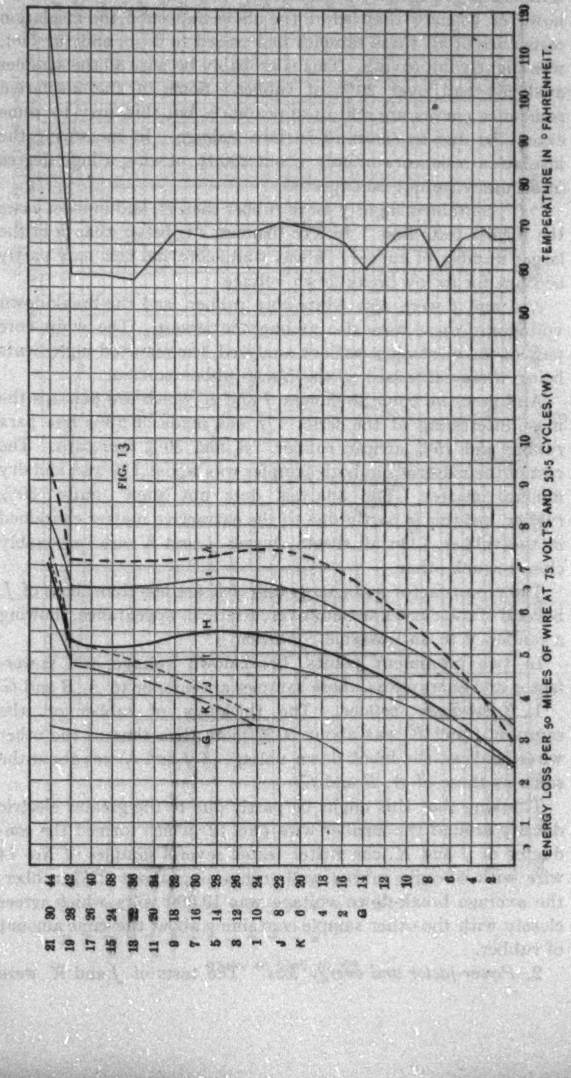


FIG. 13

TEMPERATURE IN °FAHRENHEIT.
50
60
70
80
90
100
110
120
ENERGY LOSS PER 50 MILES OF WIRE AT 75 VOLTS AND 53.5 CYCLES.(W)
1
2
3
4
5
6
7
8
9
10
G
H
I
J
K
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 G
21 19 17 15 13 11 9 7 5 3 1 J K

temperature at the end of the series. There is sufficient evidence, however, to show that before the above happened, the insulation resistance of all these samples had ceased to drop, and, in fact, was slightly improving. This is probably because all the samples analyzed had over 20% of rubber. Some of the insulation resistance curves are odd in appearance, but this may to some extent be due to errors or surface leakage. In measuring the insulation resistance of only about 200 ft. of wire, a high degree of accuracy cannot be expected.

" *I*," contained slightly more rubber than *H*, and in most cases the former tests best. In like manner, *i* is better than *h* in the larger number of curves: *h* was white-core and this may partly account for its low break-down voltage.

c, *d* and *f* were also white-core rubber, and the break-down voltages of these were also among the lowest. The white-core part of the insulation was not analyzed, the reported ingredients being those contained in the black-rubber portion.

And now, we come to curves *J* and *K* which are perhaps the most interesting of the series. *J* was made of 15% fine para rubber and 15% african rubber. *K* had 30% fine para. The rest of the materials in both samples was about 1% wax and dry mineral matter. The analysis does not show quite 30% rubber, but this is partly due to the extractive matter contained in the rubber. On all sheets, curves *J* and *K* are reasonably close to each other.

The power-factor and energy loss of *K* are less than those of *J*. Several of the curves are, however, erratic in appearance, showing a tendency to an unstable condition.

In two prominent points, break-down voltage, and power-factor and energy-loss, these samples are inferior to *A*, *B* and *G*.

1. *Break-down voltage.* The thickness of rubber on the samples *J* and *K* was about 50% more than that of the other wires, and yet the break-down voltage of *J* and *K* was about the same as those of *A*, *B* and *G*.

Thinking that this might be partly due to the greater electric density around the smaller wire (No. 12) which formed the conductor of *J* and *K*, the writer tested several samples of No. 14 wire with 51 mils rubber wall, containing about 22% rubber; the average break-down voltage was 19,000 volts, which agrees closely with the other sample containing about the same amount of rubber.

2. *Power-factor and energy loss.* The tests of *J* and *K* were

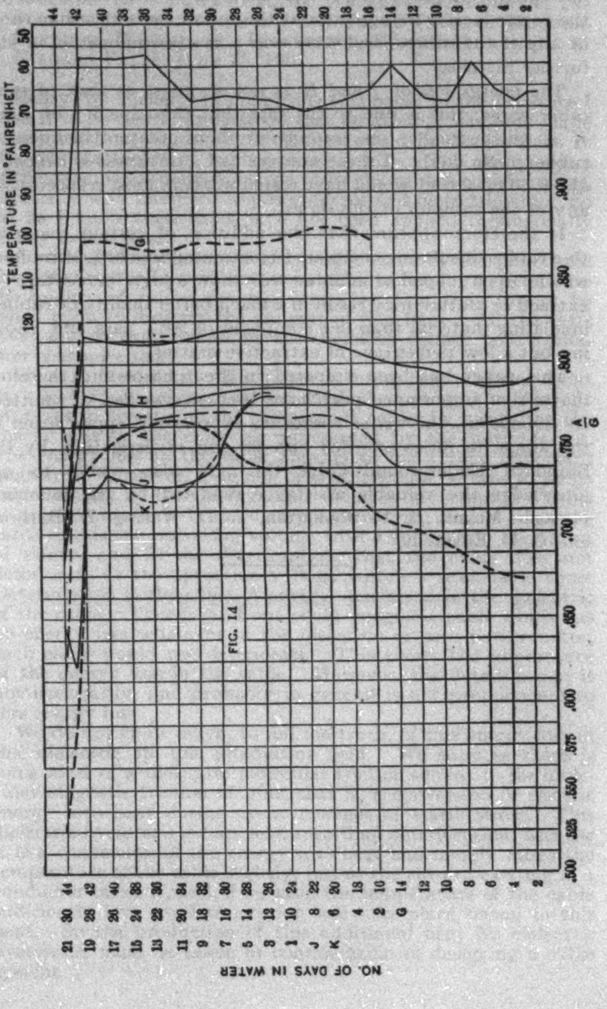

TEMPERATURE IN °FAHRENHEIT
50
60
70
80
90
100
110
120
.900
.850
.800
.750
.700
.650
.600
.575
.550
.525
.500
A/G
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 G
21 19 17 15 13 11 9 7 5 3 1 J K
NO. OF DAYS IN WATER
G
I
H
h
J
K

FIG. 14

not carried on for so long a time as those of the others, and yet the power-factors were greater at the end of the series than those of any of the others, and there was a marked indication of still further increase.

The energy-loss of *J* and *K* is not so great as that of some other wires; this is due to the fact that the capacity of *J* and *K* is much smaller on account of their greater thickness of rubber. No doubt, if these samples had a thickness of rubber of about 50 mils, they would have tested worse in most respects than any of the samples of the series.

It therefore appears that the addition of certain materials to a rubber-insulating compound (containing say 30% of rubber), which upon chemical analysis will show a high percentage of extractive matter, may result in a much better quality of rubber-insulating material than one composed of 30% para and showing but a low percentage of extractive matter.

This paper has been prepared in great haste and therefore matters of importance may have been overlooked or omitted. In conclusion, the writer wishes to express his appreciation of the ample facilities afforded him for this investigation, by the Standard Underground Cable Co. He also wishes to acknowledge the valuable assistance rendered by the following persons: Messrs. H. D. Shakarian, T. D. Waring, H. Barbour and G. D. Eustachio.

DISCUSSION ON "POWER-FACTOR, ALTERNATING-CURRENT INDUCTIVE CAPACITY, CHEMICAL AND OTHER TESTS OF RUBBER-COVERED WIRES OF DIFFERENT MANUFACTURERS," AT NIAGARA FALLS, JUNE 25, 1907

Henry W. Fisher: In presenting this paper to the Institute I wish it to be clearly understood that no attempt has been made to say anything or do anything that would be discourteous to the manufacturers of rubber-covered wire. The main object of the paper is to compare a large variety of rubber-covered wires, especially with reference to power-factor and dielectric loss. So far as I know these tests have not been applied commercially to any extent here.

A careful examination of the results given in the paper will show that power-factor tests are valuable in helping to determine the quality of rubber-covered wires, but that they cannot be relied upon to indicate the amount of fine Para. All the tests given are essential, especially the chemical, voltage, and insulation resistance tests.

Chas. P. Steinmetz: This paper is interesting in giving what may lead to an advance in our method of judging cables. It proposes to investigate the character of cables by measuring the energy loss in the cable as represented by the power-factor. The energy loss in the cable appears to me a very important quantity. However, I do not believe it would be safe to judge cables merely by this energy loss. What is important in a cable or any condenser is 1: the disrupted strength; that is, that the cable stands the operating voltage with a sufficiently high limit of safety, and 2: the deterioration, that the cable does not deteriorate at the operating voltage within a reasonable time. Deterioration is the effect of energy consumed in the dielectric of the cable, Therefore, if one could imagine a cable which has no energy loss whatever in the dielectric or zero power-factor, such cable would not deteriorate. This shows the importance of the energy loss in the cable. However, the deterioration is not necessarily, and probably in general is not proportional to this energy loss.

We do not know much, to tell the truth, of this energy loss in the dielectric in the alternating field. We suppose there is some kind of a dielectric molecular friction similar to the molecular magnetic friction of iron; that is, a conversion of electric energy into heat during cyclic changes of static stress. This dielectric hysteresis is harmless, regarding deterioration, because it is a conversion of the energy into heat and merely raises the temperature of the cable slightly, just as the current existing in a conductor raises it, and, if we keep the temperature of the cable sufficiently low, no deterioration will take place owing to this heat. So the production of this additional heat by dielectric hysteresis, must be taken in consideration in designing a cable system.

There is, however, a phenomenon, no analogy of which exists in the magnetic field; that is, a conversion of energy not directly into heat, but into chemical action, and that probably is what leads to the deterioration, the destruction of the dielectric. It is a chemical action exerted upon the dielectric proper, or upon gases included in the dielectric, either absorbed or as air bubbles, etc. If we could separate the energy converted into chemical action from the energy converted directly into heat, we could draw conclusions, the former may give us a clue to the probable life of the cable or condenser. But even then it may not give a direct estimate of the life, because the distribution of the destructive energy is all important. We may have cases in which the energy converted into chemical action, that is destructive energy, is moderately high but uniformly distributed over the whole cable, and the cable so has a good life, while in other cable in which much less energy is acting destructively, may rapidly go to pieces, because the total chemical action, although less is concentrated in a few spots, some air bubbles there weaken the dielectric, rapid oxidation of the rubber etc., takes place, and so disruption. That latter feature is well known to any one who has attempted to build electrostatic condensers for very high voltage. There the chemical energy is localized at some few spots where air bubbles have remained in the dielectric, and destroys it.

While we do not yet know much concerning the laws of energy loss in dielectrics, we know that a part of it, the dielectric hysteresis proper, probably does not vary proportionately to the square of the voltage, and so does not give a constant power-factor independent of the voltage, but a power-factor which probably decreases with increase of voltage, while from other observations and theoretical reasons it appears probable that the chemical destructive action at higher voltages increases more rapidly than the square of the voltage; that is, the power-factor increases with increasing voltage, and it appears to me, any conclusion which could be drawn from measurement of the power-factor of the cable could be drawn only if the power-factor is measured at the operating voltage, at which the cable is to be run, and that is the main objection I have to the paper, although in general I agree with the trend of it. I think that power-factor and energy measurement are made at 75 volts, if I am not mistaken. I believe they should be made at the voltage at which the cable is supposed to operate.

I wish to call attention to the statement that the condenser with the internal energy loss can be represented by a perfect condenser in series with a non-inductive resistance. I do not think that is quite correct. I think an imperfect condenser can be represented by a perfect condenser, shunted by a high resistance. If we consider the extreme case, where there is a very high loss, a series resistance would mean the wattless component of voltage is reduced thereby, which is hardly probable. In the present case it makes no difference because the non-inductive resistance is very small, compared with the remaining wattless effect, but, where there is a very considerable energy loss, I think the safer way is to put it that the imperfect condenser is represented by a perfect condenser shunted by a non-inductive conductance.

The paper certainly refers to a feature that has not always been given proper attention; that is, the importance of the energy loss in the cable, not for the sake of the efficiency of the plant, but for the sake of its possible effect on the life of the cable. One great difficulty in this matter is the method of measuring the loss, which the paper says is difficult and complicated, and not very easy to do under usual factory conditions.

E. W. Stevenson: In the early part of the paper Mr. Fisher mentions something about the change of dielectric with the temperature. I would ask him if it is an admitted fact that the smaller change of dielectric resistance due to temperature shows a higher percentage of pure para? The reason I ask this is because recently I read a specification that called for a very small change of dielectric resistance per degree of increase or decrease in temperature. That is the first time such a requirement has been called for. There has been considerable argument upon it, whether it is so or not.

Henry W. Fisher: The temperature coefficients vary with the ingredients mixed with the rubber, and probably also with the steam temperature and pressure and time of vulcanization. The coefficients are generally less the higher the percentage of fine Para rubber. The coefficients are not uniform throughout a considerable difference of temperature. In some cases the curves representing the coefficients in terms of temperature are of double curvature and sometimes single curvature. I presented curves showing these peculiarities at the Asheville meeting two years ago.

Henry G. Stott: This is a subject in which I take a great deal of interest. It seems to me that the paper starts in from the wrong point of view. A number of different types of wire are taken and analyzed as closely as possible, and then the results of various tests are given to show just how the various characteristics varied with a change in composition. I think we could get a great deal more information if the manufacturers would start out with a definite composition and increase just one ingredient at a time, and follow that up so that we could get a complete curve of variation due to various percentages of that ingredient and so on, following through with the percentage of para, various extracts, mineral matter, etc. But if we could start on a definite basis and build up first one characteristic and then another, I think we would arrive at something very definite upon which specifications could be based.

The paper on specifications for rubber-covered wires by Mr. Langan, read a little over a year ago, assumed to give such specifications. On trying to carry out the specifications enumerated, stretching tests and others, I found that the same results could be duplicated by entirely different compounds, African rubbers, mixtures of various sorts, reclaimed rubber could be made to give practically the same characteristics as 30 per cent. or 40 per cent. para rubber, and based on that I published a series of tests made on different types of compound to show how impossible it was to depend on anything at the present time except on the manufacturer's word, as to what the wire contained. Chemists all agree that it is extremely difficult, if not impossible, in any analysis to say exactly what the constitutents are in any given rubber compound.

Henry W. Fisher: I am interested in Dr. Steinmetz's remarks and fully agree with him that tests of this sort should be conducted at higher voltages. However, at the time, these tests were made the apparatus available was designed for low voltages, and the wires tested were those used generally on 100-volt lines.

It is my intention, however, soon to use higher voltages, in connection with which special apparatus like condensers, transformers, etc., will have to be designed. Probably the apparatus most difficult to obtain would be a good mica condenser of low power-factor and high capacity to operate continuously at from 6,000 to 10,000 volts.

Answering Dr. Steinmetz's criticism relative to the method of connecting the resistance in the standard condenser circuit—in getting the power-factor it is immaterial whether the resistance is in multiple or series, so long as the right formula for each case is employed. This formula for series connection was obtained from Dr. Rosa, of the Bureau of Standards and undoubtedly is correct. The resistance is used in series with the standard condenser to make the phases of the currents in the two branches of the bridge the same.

I will ask Dr. Steinmetz if he has treated this problem analytically to see if the series resistance method is incorrect, or whether he reasons from analogy that the resistance should be in multiple with the condenser?

Chas. P. Steinmetz: In the magnetic circuit, the resistance which represents the equivalent of the loss of power in the magnetic cycle, is in shunt to the circuit. In the electrostatic field we do not know enough to say whether there is a series component, but the assumption is justified that there is an electrostatic hysteresis similar to the magnetic hysteresis, and, in this case, the wattless component and the energy component should be shunted to each other, as in the case of the magnetic circuit.

I may say that, as the formula was worked out by Prof. Rosa, it was undoubtedly worked out for a case like this, where the energy quantity is very small, and where, therefore, in the first approximation, it is immaterial whether you put the resistance in series or in shunt. The question would become of importance when the energy component is considerable compared with the wattless component.

E. W. Stevenson (by letter): At the end of Mr. Fisher's paper he lays particular stress on the low breakdown voltage of the white core samples. This is a very interesting fact, especially as it comes from such an authority as Mr. Fisher. I certainly admire his courage in making the statement. I have always been strongly of the opinion that white core is nothing more than a fad. Of course it is generally understood that the white core does not contain sulphur, and therefore is used for the purpose of preventing the sulphur of vulcanization attacking the copper of the conductor. But of course all copper in rubber-covered wire is tinned, and this tinning, as everybody knows, is merely for the purpose of preventing this action, therefore if the tinning is done properly what is the use of complicating the covering process by putting on a white core?

The British navy requirements call for a pure para next to the conductor, a second covering, called a filler, in which there is no sulphur, and a third covering of vulcanized rubber on the outside, thus making three separate covers. This forces the manufacturer to use strip method of covering which, as many of us know, is not the best for all cases.

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A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

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INTERACTION OF SYNCHRONOUS MACHINES

A Graphical Solution by Means of a New Circle Diagram

BY MORGAN BROOKS

When two synchronous machines are in operation as generator and motor, the amount of power demanded of the motor causes it to assume a definite phase relation to the generator, somewhat dependent also upon their relative excitation and upon the impedance of the circuit including the two machines. When such machines are operating in parallel, there is theoretically no power to be transferred, but this ideal condition can only exist when the excitation and phase relation of the machines are identical; if these differ, even by a small amount, transfer of power must take place between generator and motor. The power required by the motor causes a certain vector difference; conversely, the presence of a vector difference points to a definite transfer of power from one machine to the other.

The object of this paper is to present a new circle diagram showing the physical relation of the quantities and conditions involved, to derive and interpret the fundamental equations, and to develop simple loci for solving graphically or numerically the problems of synchronous operation. While based upon strict mathematical analysis, it is hoped that the simplified diagram here shown will be found so direct and rational as to make the analytical method more easily understood and generally serviceable.

The elementary theory of synchronous alternating machines assumes that successive instantaneous values of electromotive force and current follow one another in a manner strictly harmonic. Oscillograph records from normal alternators so closely approximate sine-wave forms as to justify the theory. Irregularities, if considerable, indicate an unsatisfactory machine, one not amenable to simple calculations; but if slight they may usually be neglected, or the irregular wave be replaced for the purposes of calculation, where circuits have small reactance, by what is known as its "equivalent sine wave," having the same effective value.

A true sine wave is determined by the projection upon a fixed axis, usually vertical, of a uniformly rotating vector, whose length gives the value and whose period is the frequency of the harmonic quantity represented. Such a rotating vector could not be seen by the eye, and in order to make use of it an imaginary snap-shot is taken of it, giving the position of the vector at a certain instant. A picture or diagram of this sort, showing the relation of two or more machines as they exist at a given instant, illustrates the interaction of synchronous machines, and may even allow us to make satisfactory calculations as to operating conditions.

In Fig. 1 let the line *O A*, or briefly *A*, represent the electromotive force (preferably the measured or effective rather than the maximum value) of a single-phase alternator, and let *O B*, or briefly *B*, represent the value and relative position of the electromotive force of another alternator. If the machines so represented are running separately, their vectors may assume any angular relation and need not be of the same length, since the machines may not be equally excited or driven at precisely the same speed. Such a diagram would be understood to mean merely that the machines are adapted to operate together, and are running at approximately the same speed and excitation. For convenience, our snap-shot will always be taken when machine vector *A* is vertical, so that the relative difference of vector position is confined to *B*. If the two machines represented in Fig. 1 are about to be connected in parallel, it is understood that the vectors should be found nearly coincident before the paralleling switch is closed, after which the machines should continue to run with vectors coincident, or nearly so. If hunting should exist, its vector representation would be in the oscillating position of the two vectors, now one ahead slightly, now the other, their possible separation indicating the greatest amplitude of the hunting action. The position of *B* with reference to *A* in Fig. 1 might represent either an extreme position of hunting, or a limiting position for switching into parallel. If two machines, equally excited, were thrown into parallel when their vectors were coincident connection being understood both at *O* and at *A B*, no current would flow in the local circuit; but if the machine vectors were

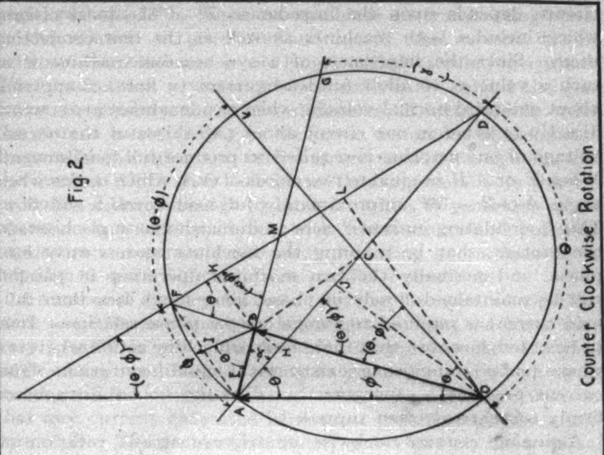
Fig. 2
Counter Clockwise Rotation
A
B
C
D
E
F
G
H
I
J
K
L
M
O
V
θ
φ
(θ-φ)
(θ+φ)
(x-y)
x

FIG. 2—Circle diagram

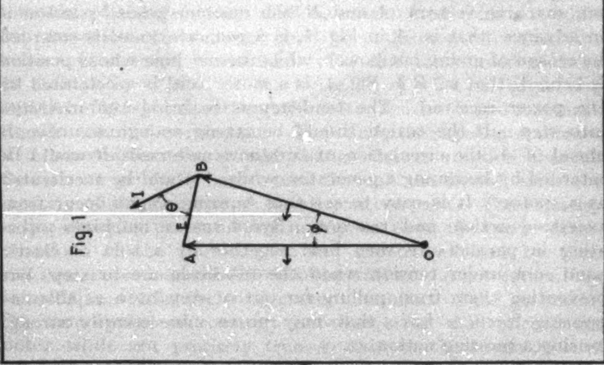
Fig. 1
A
B
O
E
I
θ
φ

FIG. 1—Vector diagram

a little out of exact coincidence, as *A* and *B* in Fig. 1, then a current would flow between the machines, owing to the vector-difference voltage, *A B*, existing in the local circuit, since it is possible to take A-B to represent the vector difference of the voltage O-A of machine A, and voltage O-B of machine B. A-B represents the only electromotive force acting and we may use E in place of A-B. The current, I, that E will drive through the circuit, depends upon the impedance, Z, of the local circuit, which includes both machines as well as the line connecting them. Since the impedance of a synchronous machine is of such a value as to allow full-load current to flow on applying about one-third normal voltage, when two machines are coupled directly together in one circuit about two-thirds of the normal voltage of one machine is required to produce full-load current. When E, or A-B, is equal to two-thirds of O-A, which occurs when angle A-O-B = 39°, approximately full-load current will flow. This " circulating current " acts to diminish the angle between the vectors; that is, to bring the machines more nearly into phase, and normally the two machines operating in parallel will be maintained closely in phase, since much less than full-load current is required to compel proper phase relation. It is to be noted, however, that there is no compelling action whatever when phase coincidence exists with equal excitation. The current prevents a separation but does not hold the machines firmly together as often supposed.

Assuming counter-clockwise or trigonometrical rotation of our machine vectors, A and B, the machine whose position is in advance; that is, A in Fig. 1, is a generator, and is retarded by reason of giving out power; while the machine whose position is behind; that is, B in Fig. 1, is a motor, and is accelerated by the power received. The tendency is to bring the machines into step. If the action should be strong enough to drive B ahead of A, the circulation of current is reversed; B would be retarded by becoming a generator, while A would be accelerated as a motor. It is easy to see that hunting might occur from excessive action and reaction. Synchronous machines operating in parallel are then held together by a sort of elastic band, not under tension when the machines are in step, but preventing them from pulling far out of step by a rapidly increasing force, a force that may prove unnecessarily strong, causing a hunting action.

The value of the synchronizing force under working conditions may be calculated, as will be shown. When two machines are operating together under light load, if one loses its driving power it will fall behind its normal parallel vector position only just far enough to enable it to receive current to maintain it in step. No noticeable change in running occurs. It is often supposed that when a generator becomes a motor it falls behind 180 electrical degrees, while in fact it falls behind a very small angle, perhaps 10°. When two machines are transmitting power in the relation of generator and motor, the current flowing between the machines is no longer called circulating current. The motor takes a vector position sufficiently behind the generator to produce the vector difference, E, required to drive the current corresponding to the power demanded of the motor. In parallel operation the machines are usually contiguous, and the current which may "circulate" has in general only the impedance of the machines to limit it; while in generator-motor operation a transmission line with transformers and potential regulators is commonly included, producing a condition as to impedance quite different from parallel connection.

A number of synchronous machines may be operated together, some as generators and some as motors, and the machines may vary greatly in size. To simplify the problem two identical single-phase machines, A acting as generator and B acting as motor, will be considered as connected in a single circuit, so that any current generated in A must pass through the armature of B. The problem commonly provides that the terminal potential of the generator shall be maintained constant, while the excitation of the motor shall be under control. Constant frequency or speed is assumed. The line is assumed to have its resistance, r, and its reactance, x, $[= 2 \pi f L$ neglecting capacity effects] constant, and the motor resistance and reactance are also assumed as constant. To include the capacity reactance of a transmission line would change the assumption that all the current generated must pass through the motor, since the capacity of the line acts as an alternative path. The capacity or line-charging current being nearly wattless, the power determinations of the problem are not greatly affected by their omission under load conditions of operation. A correction may be made to obtain the total current required of the generator. The assumption of constant impedance for the synchronous motor, while not precisely true, is akin to the assumption of constant friction loss in engine operation. Except for abnormal conditions, it is believed that no great error is thus introduced. This gives the ratio of R to Z $[R/Z = \cos \theta]$, or the power-factor of the circuit as a known constant, and enables a simple diagram to be plotted.

The regular equations of synchronous operation will now be developed by means of Fig. 2, which differs from Fig. 1 only in the drawing of a circle, whose diameter is $A/\cos\theta$, so centered as to make A a chord, in the extension of vectors B and E to intersect the reference circle at F and G, and in projection of the electromotive-force vectors, A B, and E upon the circle's diameter $A\,D$ and upon the chord $F\,D$, the utility of which projections will presently appear.

NOTATION

A, short for $O\,A$, a vector representing generator terminal voltage, assumed to be kept constant. Vertical position chosen for convenience.

B, short for $O\,B$, a vector representing the induced motor voltage, variable both as to length and direction. Position shown in Fig. 2 indicates any position whatever in its relation to A.

E, or $A\,B$, a vector representing the vector difference of A and B, or the net voltage acting in the circuit which includes the motor.

I, the current produced by E. $I = E/Z$.

R, the resistance of the motor and circuit.

X, $[\,= 2\,\pi\,f\,L]$ the reactance of the motor and circuit.

$Z = \sqrt{R^2 + X^2}$ the impedance of the motor and circuit.

θ, the angle between E and I. It is a constant determined by the condition,

$\cos\theta = R/Z$, the power-factor of the circuit, often confused with $\cos\alpha$, below.

θ appears in Fig. 2 as the angle made by the lines $A\,C$ and $O\,C$ with vector A; the reference circle is determined by having their intersection C as its center.

ϕ, the angle between A and B, a variable, assumed positive when B lags behind A as shown, the usual condition of operation, when B is a motor.

$\theta + \phi$, the angle between B and $A\,C$, since θ is the angle between $A\,C$ and A, and ϕ that between A and B.

$\theta - \phi$, the angle between A and the chord $F\,D$, which lags behind $A\,C\,D$ by the angle ϕ.

α, the angle between A and I, a variable, considered positive when I lags behind A due to B being under-excited.

$\cos\alpha$, the generator power-factor, sometimes confused with $\cos\theta$ above.

The angle α, appears on the reference diagram as the angle B A C, or the angle between $A\ C$ and E. A lags $\theta°$ behind $A\ C$ by construction. I lags $\theta°$ behind E by definition, hence it is seen that angle B A C is also the zero angle of I to A. Normal excitation reduces this angle to O, and $\cos a = 1$.

$\alpha - \phi$. the angle between B and I, since B lags $\phi°$ behind A. This angle is usually negative, as α is normally small, that is, I usually leads B.

The angle $\alpha - \phi$ appears on the reference diagram as $A\ M\ F$, or the angle between E and chord $F\ D$.

$\cos(\alpha - \phi) = \cos(\phi - \alpha)$ might be called the motor power-factor.

These angles are conveniently measured by half the intercepted arcs, as indicated in the diagram, Fig. 2.

P', the power output of the generator $= A\ I \cos\alpha$.
P'', the power intake of the motor $= B\ I \cos(\alpha - \phi)$.

The diagrams are calculated for values as follows:

$A = 1000$ volts, and
$R = 1$ ohm.

Where $\theta = 45°$, $X = 1$ ohm also, and $Z = 1.41$ ohm
" $\theta = 60°$, $X = 1.73$ ohm, and $Z = 2$ ohms.
" $\theta = 75°$, $X = 3.73$ ohms, and $Z = 3.86$ ohms.

With the above data, the power figures in Figs. 4b and 6 are in kilowatts.

From the projections of A, B and E on diameter $A\ D$, Fig. 2, it is evident that $A\ J - H\ J = A\ H$, or as

$$A \cos\theta - B \cos(\theta + \phi) = E \cos\alpha \qquad (1)$$

multiplying by A/Z,

$$\frac{A^2 \cos\theta - A\ B \cos(\theta + \phi)}{Z} = A \frac{E}{Z} \cos\alpha = A\ I \cos\alpha = P' \qquad (2)$$

the generator output.

From the projections of A. B and E upon the chord $F\ D$, it is evident that

$$F\ L - K\ L = F\ K, \text{ or}$$

$$A \cos(\theta - \phi) - B \cos\theta = E \cos(\alpha - \phi). \qquad (3)$$

Multiplying by B/Z,

$$\frac{A\,B\cos(\theta-\phi)-B^2\cos\theta}{Z}=B\frac{E}{Z}\cos(\alpha-\phi)$$

$$=B\,I\cos(\alpha-\phi)=P'' \qquad (4)$$

the motor intake.

The difference between generator output and motor intake is lost in heat, as with direct-current machines; this is shown in equations (2) and (4):

$$P'-P''=\frac{A^2\cos\theta+B^2\cos\theta-2\,A\,B\cos\theta\cos\phi}{Z}$$

$$=\frac{R}{Z^2}[A^2+B^2-2\,A\,B\cos\phi]=\frac{R\,E^2}{Z^2}=R\,I^2 \qquad (5)$$

Equations (2), (4) and (5) above, are the well-known fundamental equations of synchronous machine operation, and, while derived from the relation of two machines operating as generator and motor, they apply to two machines in parallel operation, provided the current be now understood as circulating current only.*

Power Output.—

Interpretation of equation (2) above,

$$P'=A\frac{E}{Z}\cos\alpha$$

or,

$$E\cos\alpha=\frac{P'\,Z}{A},$$

a constant for any given value of generator output, P'. Hence, for constant P', $E\cos\alpha$, the projection of E on diameter $A\,D$, is constant, or the locus of B lies in a line perpendicular to $A\,D$, such as $N\,Q$, Fig. 3. The equation is the regular polar equation of a straight line. The power output of generator P' is directly proportional to the length of the projection on $A\,C$, and hence measured thereby. Parallel lines drawn at equal distances apart, serve as a chart for reading the value of P' when the position of B is known.

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*Compare Franklin & Williamson, Alternating Currents, page 189. Second Edition.

With $P' = O$, the locus becomes the tangent to the reference circle at A. For positive values of P', that is, generator action, the parallels are to the right of this tangent; for negative values of P'', that is, for motor action, reversing the ordinary conditions of the problem, parallels may be drawn to the left of the tangent, shown in dotted lines in Fig. 3. For such positions of B making A a motor, it is evident that machine B must become the generator, as will be demonstrated under power intake. Mathematically there is no limit to the possible values of P', either positive or negative. Operating values are limited by the possible excitation of B, and normal operating values of P' would not ordinarily exceed corresponding values of P'', the motor intake, by more than 25%, the condition for 80% efficiency. Excessive values of P' will exist momentarily in synchronizing two machines if the switch be closed at an unfavorable vector position.

Power Intake.

Interpretation of equation (4),

$$P'' = \frac{A\,B\cos(\theta-\phi) - B^2\cos\theta}{Z}$$

transposing,

$$B^2 - B\frac{A}{\cos\theta}\cos(\theta-\phi) = -\frac{P''Z}{\cos\theta} \qquad (6)$$

a constant for given intake, P''. This equation is the polar equation of a circle, as may readily be seen from Fig. 2 as follows:

Substituting for $A/\cos\theta$ its value, $2\,(O\,C)$, adding $(O\,C)^2$ to both members, and writing $(O\,B)$ for B,

$$(O\,C)^2 + (O\,B)^2 - 2\,(O\,C)\,(O\,B)\cos(\theta-\phi) = (O\,C)^2 - \frac{P''Z}{\cos\theta}$$

The first member evidently gives the remaining side of the triangle O C B, and we have

$$(C\,B)^2 = (O\,C)^2 - \frac{P''Z}{\cos\theta} \text{ or } (C\,B) = \sqrt{(O\,C)^2 - \frac{P''Z}{\cos\theta}} \qquad (7)$$

The second member is constant for constant load on motor, hence, for such load, the locus of B lies in a circle centered at C and of radius determined by the radical.

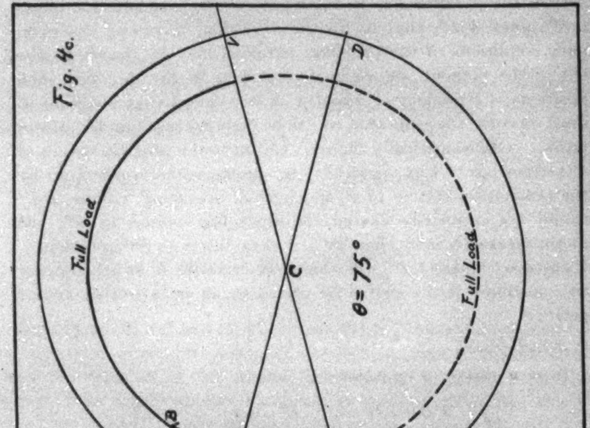
Fig. 4c.
V
D
Full Load
C
θ = 75°
Full Load
B
B
B
θ
A
O
Fig. 4a.
V
D
B'
B'
B'
Half Load
C
θ = 45°
Full Load
A
B
O
Fig. 4b.
500
400
300
200
100
180
160
210
240
270
C
θ = 60°
Full Load
V
D
A
O

FIG. 4a—Locus of B for constant motor intake. FIG. 4b—Same for $\theta = 60°$. FIG. 4c—Same for $\theta = 75°$

For $P'' = O$, B lies in the circumference of the reference circle, which has C for its center, and $O\,C$ for radius. This is evident since I lags 90° behind B for any point in the circumference. There may be a large current, and the $R\,I^2$ losses are supplied by the generated power P'.

Negative values of P'', meaning that machine B has its function reversed and acts as a generator, bring B necessarily outside the reference circle, as at B' and B'', Fig. 4*a*. There is no mathematical limit for such external values. If the position of B is also to the left of the tangent ST, as at B', the function of machine A is also reversed, being a motor, while, if the position lies to the right of the tangent, $S\,T$, but outside the circle, as at B'', A remains a generator, and both machines act as generators to supply the large $R\,I^2$ losses of such a position.

Positive values of P'', that is, normal motor action, give loci for B within the reference circle, the value of $C\,B$ diminishing with increasing load, as can be seen from equation (7). The locus for any given load is a definite circle, whose radius is readily determined. Loci differing by equal amounts, as loci for 50, 100, 150, and 200 kilowatts, will be separated in such manner as to have equal areas in the rings included between successive loci. In equation (7), if $\dfrac{P''\,Z}{\cos\theta}$ exceeds the value of $O\,C^2$, the value of $C\,B$ is an imaginary quantity; that is, the motor must fall out of step when such an excessive load is applied.

$$\frac{P''\,Z}{\cos\theta} = (O\,C)^2$$

is the limiting case, the maximum load which the motor will theoretically carry. $C\,B = 0$; that is, the point C is the locus of B for this load, which is several times full load. At this point $B = O\,C$, and $P'' = \dfrac{B^2\cos\theta}{Z}$. Equation (2) gives the generator power for the same point as follows:

$$P' = A\cos\alpha\,\frac{E}{Z} = \frac{A\,B}{Z} = 2\,B^2\,\frac{\cos\theta}{Z}$$

It will be noted that this is just twice the value of P'', showing 50% efficiency, as with direct-current motors at maximum load. Loci for normal loads are circles but little smaller than the reference circle.

Efficiency.

Interpretation of equation (5),

$$P' - P'' = \frac{R E^2}{Z^2}$$

Dividing by P', which by equation (2) $= A\,E/Z \cos \alpha$

$$1 - \frac{P''}{P'} = \frac{E\,R}{Z\,A \cos \alpha} = \frac{E \cos \theta}{A \cos \alpha}.$$

Transposing,

$$\frac{A}{\cos \theta} \left(1 - \frac{P''}{P'}\right) = \frac{E}{\cos \alpha} \tag{8}$$

For a given value of efficiency, P''/P', the first member becomes constant, and the equation is the polar equation of a circle. For different efficiencies, circles of different diameters are found, but all pass through the common point A, which is common to all positions of E; they are all tangent to S T at A.

For efficiency = 1 the locus of B is reduced to the point A.

For efficiency = 0.9 the locus of B lies in a circle whose diameter is $0.1\,A/\cos \alpha$.

For efficiency = 0.8 the locus of B lies in a circle whose diameter is $0.2\,A/\cos \alpha$.

For efficiency = 0.5 the locus of B lies in a circle whose diameter is $0.5\,A/\cos \alpha$.

For efficiency = 0 the locus of B lies in a circle whose diameter is $1.\,A/\cos \alpha$.

These loci are sufficient to indicate any desired efficiency. For zero efficiency the locus coincides with the reference circle, which is also the locus of zero intake of machine B. Fig. 5 shows loci for given efficiencies as marked.

Heat Loss. Equation (5), $P' - P'' = R\,I^2$, shows that the machine A not only furnishes the power P'' to machine B, but also supplies the heat losses $R\,I^2$ of the circuit. These losses should include the core losses of transformer and motor, and for better interpretation the second member might read $R\,I^2 + H$, meaning by H the core losses, which are approximately constant and independent of current. It is seen that the $R\,I^2$ losses proper, or copper losses, assuming R as constant, depend upon I^2, hence

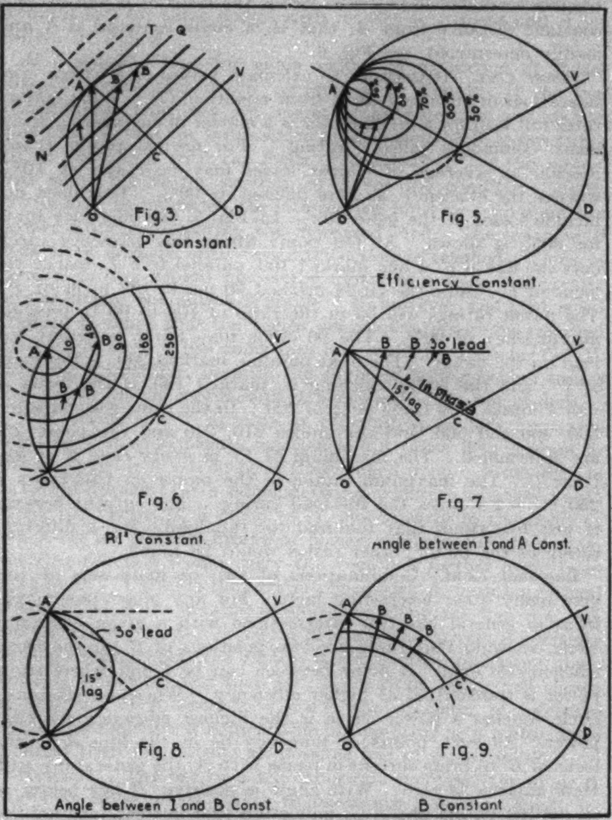
T
Q
V
A
B
B
U
N
C
O
D
Fig. 3.
P' Constant.
A
V
70%
60%
50%
C
O
D
Fig. 5.
Efficiency Constant.
A
10
40
B
90
160
250
V
B
B
C
O
D
Fig. 6
RI² Constant.
A
B
B 30° lead
B
V
In Phase
15° lag
C
O
D
Fig 7
Angle between I and A Const.
A
V
30° lead
15° lag
C
O
D
Fig. 8.
Angle between I and B Const
A
B
B
B
V
C
O
D
Fig. 9.
B Constant

FIG. 3—Locus of *B* for constant generator output
FIG. 5—Locus of *B* for constant efficiency
FIG. 6.—Locus of *B* for constant I^2R loss
FIG. 7—Locus of *B* for given current angle referred to generator
FIG. 8—Locus of *B* for current referred to motor
FIG. 9—Locus of *B*, when of constant value.

upon I, and upon E, which produces I. For any given loss, whether or not including core losses, the locus of B will be at a constant distance from A, that is, a circle centered at A and readily determined; see Fig. 6.

Power Loci. It is easier to calculate values of P'' from considerations of efficiency, than from equation (7). What constitutes full load for a given motor is a matter of engineering judgment, commonly called "rating." For normal power transmission an average of copper losses may be taken at 10%, whence the efficiency, as here defined, is 90%. This does not include losses in the generator. In Fig. 5, the efficiency locus for 90% is shown. At the point where this efficiency circle cuts the line $A\,C$, a line marked 100, parallel to $S\,T$, marks the locus of P', while the circle marked 90 marks the locus of P''. The power ratings will be in the ratio of 100 to 90 to produce an efficiency of 90%. The 90 circle may fairly represent full load on the motor. The next parallel, marked 200, is the locus of P', and the circle touching it, marked 160, is the locus of motor intake, 160 being 80% of 200. In the same way parallels 300, 400 and 500, and the circles 210, 240 and the point 250 are determined. The maximum of P'' in every case is at the point C. The maximum intake of the motor on this basis is $250/90 = 2.8$ times the full-load rating. The current flowing is just five times that required for full load. By a different rating of the motor, other ratios would be found.

Lag and Lead. Combinations of two or more sets of loci give many other interesting facts. For any given power, the locus in general has two intersections with a given efficiency circle, showing that there are two positions of B for the same efficiency of load. A point between can be found where more power is transmitted at higher efficiency. Where an efficiency circle touches a power circle is the highest efficiency for that power. All such points of tangency lie in the line $A\,C$, the locus of B, to bring current in phase with A, the generator e.m.f. Here angle α is zero. With angle α positive, B lies below or to the left of the line $A\,C$, indicating that current lags behind the vector A; with angle α negative, B lies above or to the right of $A\,C$, causing current to lead vector A. The locus for any required lag or lead is easily drawn by merely passing a line through A, making the desired angle with $A\,C$, the normal line. Such loci are shown in Fig. 7.

The loci for current in phase with B, or at any desired angle with B, are drawn almost as easily. They are arcs of circles passing through A and O, and tangent to the corresponding straight loci for same angles with respect to current and A, as shown in Fig. 8.

B Constant. Loci for given values of excitation of B are simply circles with radius centered at O, Fig. 9. If the two synchronous machines are operating as generator and motor, it is evident that the intersection of such locus of B, representing given excitation with the locus of the load P'' of the motor, will show the vector position of B for the conditions given. If the load be increased, the intersection must be with a smaller power circle representing the increased load. The machine B falls back slightly until this intersection is reached. Since in general falling behind places the motor in a region of greater power intake, the action is stable. If, however, the load is increased so much that the vector does not intersect the required load circle until it has come into line with the diameter $O\ C\ V$, running is unstable, because the slightest falling behind brings less power to the motor, and it necessarily falls out of step.

The diameter $O\ V$ appears as a definite boundary for stable running, but as armature reaction is not taken into account in the analysis, it is not to be entirely relied upon. From Fig. 4a it would appear that a demagnetizing armature reaction would bring the vector B, if equal to A, more nearly to the point C, the locus for greatest intake of power; while in Fig. 4c demagnetizing reaction would carry the vector B further away from that point. Currents that are in phase with A, meaning normal positions of B for maximum efficiency along the line $A\ C$, are demagnetizing for B. Since the action of the current is normally demagnetizing upon the motor, a satisfactory operating angle for θ is somewhat less than 60°, a condition fairly well shown in Fig. 2. If B exceeds $A/\cos\theta$, the diameter of reference circle, the machine B is incapable of operating as a motor, since B must then fall outside all possible loci of power intake.

Reactors. The use of a reactance coil increases the angle θ. For long lines, where owing to resistance θ may be small, its use is justified. For proper operation it is easy to use too powerful a regulator, as seen from Fig. 4c where $\theta = 75°$. Here it is only possible to obtain the large values of motor intake by exciting the motor greatly beyond the value of A. Hence if only moderately excited, the motor would fall out of step too easily. Effort should be made to make θ about 55° to avoid manipulation of field rheostats. Where the transmission line is short, the angle will probably exceed this, but to reduce the angle by the introduction of resistance would of course be very objectionable, as it would decrease the efficiency. It might be possible to select a machine with lower inductance than usual for such short line conditions, as for operation in parallel.

Condenser Action. The above paragraph must not be confused with the question of over-excitation to produce the so-called "condenser effect," giving a leading current in respect to A. Over-excitation makes the angle α negative; that is, it is excitation carrying vector B beyond the line $A\,C$, the normal excitation locus. It is seen that this is not a constant excitation, but depends upon the other conditions of the circuit, load, etc. With θ greater than 60°, over-excitation means as a rule, excitation of B greater than that of A; while with θ less than 60°, B may be over-excited, and yet be less excited than A. Under-excitation is less than normal, making the current lag due to a positive angle α. It is possible to have under-excitation, and yet an excitation greater than that of the generator. This may be the case at heavy loads with a large angle θ. It may be remarked that "condenser effect" is not a true capacity action, since such effect would not tend to increase the triple-frequency component of current, as would be the case with true capacity.

Converters. Synchronous converters may be compound-wound, and so operate successfully on circuits where the angle θ is considerably more than 60°. For short lines, where θ is large, the converter series-winding should be cumulatively connected, to increase the excitation when loaded. This will be the proper condition for such a machine serving lighting circuits, where over-compounding is desired. For long lines powerful reactors may be required to make the use of compound-wound converters feasible. For railway service, where precision of direct-current voltage is less important, it may be satisfactory in the case of a low value of angle θ to reverse the series-winding, making it differential. Operation at least would be more satisfactory. A shunt-wound converter is often preferred, and should act well on moderately long lines. Diagrams for large and small angles θ show why there has been a spirited discussion of the relative advantages of cumulative and differentia connection of the series-winding in converters, the difference in action being due to external conditions.

Synchronizing. The constants determining the diagram for showing the behavior of synchronous machines in operation, even under the abnormal condition of falling out of step, are not applicable in making a diagram to predict the initial circulating current upon connecting the same machines in parallel. If two machines are pulled out of step without opening the circuit, it is unusual for any damage to the machines to result, although they pass through all possible phase relations. Yet experience proves that it is unsafe to close a paralleling switch except at or near coincidence of phase. The reactance of an inductive circuit upon first closing the switch depends upon the coil-winding, as if it were without iron, while as soon as the core becomes synchronized full "synchronous reactance" takes effect. The initial current is several times that which would flow at corresponding unfavorable phase position under operating conditions and lasts long enough to produce electrical and mechanical strains which sometimes result in disaster. By using a value for Z, the impedance, perhaps only 15 to 25 per cent. of normal, and a correspondingly small angle θ, a diagram may be constructed that will properly indicate the dangers of imperfect synchronizing.

For safe and effective synchronizing, the circuit may be first closed through a coreless reactance coil of moderate dimensions, as explained in a paper entitled "The Self-synchronizing of Alternators," presented by Mr. M. K. Akers and myself before the Institute in May, 1906. The diagram for showing self-synchronizing employs a value for Z about twice the normal and a large angle θ, and shows that shocks may be eliminated without reducing the useful synchronizing power in the same degree.

Synchronizing Power. The synchronizing power, tending to bring two machines into phase, may be derived from equations (2) and (4).

Equation (2)

$$P' = 1/Z\,[A^2 \cos\theta - A\,B\,(\cos\theta\cos\phi - \sin\theta\sin\phi)]$$

P' positive shows that the load upon machine A tends to retard it.

Equation (4)

$$P'' = 1/Z\,[A\,B\,(\cos\theta\cos\phi + \sin\theta\sin\phi) - B^2\cos\theta]$$

P'' positive shows that the driving upon machine B tends to accelerate it. With P' and P'' both positive, or both negative, the machines are forced together with a power found by adding the two equations:

$$P' + P'' = 1/Z\,[(A^2 - B^2)\cos\theta + 2\,A\,B\sin\theta\sin\phi] \qquad (9)$$

The first term of the second member appears to be negligible, not only because B is usually about equal to A, but also because $\cos\theta$ is small. The synchronizing power is often taken as

$$1/Z\,[2\,A\,B\sin\theta\sin\phi] \qquad (10)$$

If ϕ, the angle between the machine vectors, is the only variable, the value of (10) varies with $\sin\phi$. There is no power acting to hold the machines together, but only to prevent them from moving apart. The effect is a maximum at $\phi = 90°$, and diminishes up to the unstable position of 180°, where it is again zero. The effect, apparently negative beyond 180°, means that the action is to increase the angle toward 360° or 0°.

The above discussion concerns itself only with synchronizing forces. The first term of equation (8) appears negligible, yet its derivation from equation (2) and (4) shows that $1/Z\,[A^2\cos\theta]$ and $1/Z\,[-B^2\cos\theta]$ represent powers acting in the same sense, that is, to retard both machines, A and B.

With angle θ large, as in normal operation, the retarding powers are small, but with Z and angle θ both small, the condition which exists momentarily at the instant of switch-closing, both machines may be so suddenly retarded as to wreck them, since under the condition of small value of θ the braking effect is at its maximum, and the "$A\ B$" terms of equations (2) and (4) are a minimum. When coreless reactors are used, it is impossible for Z and θ to be small, even momentarily, and the shock to the machines is prevented. No synchronizing effect is obtained without some reactance. The effect is a maximum for large angles of θ. Introducing reactance to increase the angle θ means also an increase in the value of Z, which might result in limiting the current too much. A satisfactory compromise may be effected by trial, but the diagram will indicate readily the proper value of reactance to employ.

There should be a distinction drawn between paralleling alternators, and synchronizing a motor or converter with a distant generator. To bring into action an additional generator, especially when the object is to relieve an overload on the machines in operation, care should be taken not to close the switch with the incoming machine in motor, or "B"-vector, position. This will be best accomplished by having the incoming machine running slightly above synchronous speed, and closing the switch not too early. For placing a converter in service, on the other hand, the incoming motor is to receive power, and should not be switched in as a generator or in "A"-vector position. This is best accomplished by having the machine running slightly below synchronous speed, and closing the switch not too early.

Comparison with "V-Curves." The loci of B for various powers as shown in Figs. 4a, 4b, and 4c correspond precisely with the irregular shaped curves called "phase characteristics" or more commonly "V-curves." In the circle diagram, excitation and current are measured by proper scales radially from O and from A (a double polar diagram). In the usual form of V-curves, the plotting is by rectilinear coördinates. The circle diagram may be rapidly constructed by ruler and compasses, while the V-curves have to be calculated and then carefully plotted. That they are identical will be evident to anyone comparing the diagrams. If the curves are derived from experiment, two observations at given load will suffice to determine the circle with considerable accuracy, while a multitude of observations are needed to prepare a good V-curve. Of course not all observations will fall accurately in an exact circle, but the moderate deviation of normal power loci shows the essential reliability of the circles. It seems possible that a few observations carefully plotted in a circle diagram will serve to determine the "constants" of a transmission line, or of a machine, even better than the usual "synchronous impedance" tests. The method has the advantage of making the measurements under operating conditions.

The use of the circle diagram is not confined to two synchronous machines of single phase. Two or three phases may be represented. Moreover, the diagram may be applied to a non-motor load, such as a transformer with any sort of load on the secondary. It suggests a method of graphically estimating the angular phase difference between the secondaries of transformers used for different services, or between the primary and secondary of a single transformer, and at all loads. In the case of a transformer, the angle θ changes greatly with the load, and several diagrams might be required where one would suffice in synchronous machine operation. Indeed the use of previously prepared diagrams, or charts, outlined for different values of θ would make the rapid graphical solution of synchronous problems a pleasure instead of a task. The calculations and diagrams assume pure sine curves of electromotive force and current, and some allowance may be required where these curves are distorted.

That the vector relations shown by the circle diagram actually exist, at least approximately, has been recently shown by a mechanical phase indicator attached to two machines running in parallel. The problems involved in the operation of alternating-current machines are often obscure, since the real forces are not subject to direct measurement, and it is hoped that this presentation of the circle diagram will serve a useful purpose in the interpretation of the interaction of synchronous machines.

DISCUSSION ON "INTERACTION OF SYNCHRONOUS MACHINES", AT NIAGARA FALLS, N. Y., JUNE 25, 1907.

E. J. Berg: Any paper which tells in a simple way how to calculate the characteristics of two machines in parallel is valuable, especially when the equations or diagrams give the synchronizing power. From this we can determine the stability and the natural period of the machine, in other words we can predict something about its hunting tendencies. I doubt, however, if this paper will give this information and I ask Professor Brooks for some explanations. Professor Brooks uses the reactance and the resistance in the total circuit. It must be remembered that machines having the same synchronous impedance, which means substantially the same synchronous reactance, have widely different characteristics. For instance, a machine of definite pole construction and a given synchronous impedance may have an angular displacement of the armature at full load of 15 degrees, whereas another machine of the wound rotor type having substantially uniform magnetic reluctance may have 30 degrees displacement with the same impedance. It is obvious therefore, that any calculations based upon the reactance are of little value in determining its characteristics.

I hope that I am mistaken in thus interpreting the paper and that Professor Brooks can explain that he has taken into consideration not only the true reactance of the armature, but the armature reaction, that is the demagnetizing or magnetizing effect of the armature current on the field.

Chas. P. Steinmetz: I agree with Mr. Berg that these diagrams, and also the original diagram of mine that has been referred to, apply not to existing but to ideal machines. To illustrate; with change of field excitation the current rises—on one side leading, on the other side lagging: but they are not suitable to predetermine exact values, because they apply to a machine in which the reactance is constant, the armature reaction constant, the magnetic inductance, as brought out by Mr. Berg, constant in all directions. Such machines do not exist. Try experimentally to reproduce the diagrams I gave in my paper many years ago and you find near the non-inductive load, near the minimum point, you get about the same shape, but toward much lower or higher excitation you get values which may not be exactly the same as calculated.

For higher values of excitation, the experimental curve more and more deviates from the calculated, due to magnetic saturation. For low values of excitation, the curve should bend back before reaching the zero line of voltage. Instead of this, the experimental curve can sometimes be made to cross the zero line. If at constant impressed voltage you gradually lower the field excitation from that corresponding to minimum current down to zero, and then reverse the field, the machine keeps in step and you may bring up the field in opposite direction, until you have a very high reversed field excitation, and still the machine runs in the same step, with the armature reaction producing the field against the opposing magnetomotive force of the field circuit, until suddenly the machine slips one pole back and with the same field excitation, everything remaining the same, the current drops down to the value which corresponds to the positive value of excitation. Now, that no diagram shows because it is the effect of the asymmetrical magnetic structure, that is the magnetic flux is not in line with the resultant magnetomotive force, but differs therefrom by a certain angle, being closer to the center line of the field pole, and this feature throws any simple calculation out, and requires a much more complicated system of diagrams in which you have to consider the two separate components of magnetic inductance, and of armature reaction. The reactance is not a constant, but a function of the position, has different values in two directions at right angles to each other and the magnetic reluctance of the circuit also has two values. You must divide the system into two components, which can be done, but makes it a little more complicated.

Comfort A. Adams (by letter): Without wishing to subtract in any way from the credit due Professor Brooks for his very interesting paper on "The Interaction of Synchronous Machines", it is only fair to state that the principle diagrams there described were published by Professor Blondel in 1895 in "L'Industrie Electrique", and later in his book on "Synchronous Motors". The writer has used the Blondel diagram for the last twelve years in his classes and has found it a great aid in making clear the operation of synchronous machinery. He therefore appreciates most highly the interesting additions to this diagram made by Professor Brooks.

The quantitative relations between the armature resistance and reactance shown in this paper lead one to assume that the *leakage reactance* was chosen in place of the *synchronons reactance* which should have been employed.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

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PROTECTIVE APPARATUS ENGINEERING

BY E. E. F. CREIGHTON

The main object of this paper is to describe the methods which have been in use in the development of lightning apparatus, so that some or all of these methods may be adopted or recommended as standard in the investigation of the value of any particular apparatus. As an introduction, it is pertinent to point out the differences and identities in the operation of the arrester in test as compared with its operation in actual service. Generators, motors, arc lights, practically all electrical apparatus except lightning-arresters—are tested under the conditions, under which they are to operate. The lightning-arrester in service comes into action only intermittently, with long intervals between operations, and each operation is under conditions more or less different from the previous ones. It protects, fails, or is destroyed according to its adaptation to meet the imposed conditions. The arrester may operate for years before it encounters conditions which it is incapable of meeting. The conditions which caused the failure are usually unknown, therefore little or no progress can be made in the design without studying the actual conditions which caused the failure of the arrester. Since this cannot be done at present with cloud lightning, we must experiment with artificial lightning in the laboratory until this condition causing failure is found. Simply noting whether an arrester fails and then making an adjustment, elimination, or addition of parts of the arrester is a cut-and-try method and has already been carried to the limit of its efficacy in the development of protective apparatus.

In making a plea for the recognition of the value of laboratory tests, it is pertinent to look at the subject from several viewpoints. Lightning-arresters are but auxiliary devices to the large expensive machines of electrical transmission systems and the receipts therefrom to the manufacturer are small in proportion. The successful and continuous operation of electrical systems, however, depends greatly upon the efficiency of the protective devices. Great expenditures have been made in the development of protective apparatus, not on account of the intrinsic commercial value of the arrester business, but on account of the broader scope it gives to the electrical industries. Station managers should realize that to them has been given each year the very best apparatus that could be developed, and that the manufacturer of large apparatus is even more desirous than they to install an arrester which operates perfectly. Failures of arresters are comparatively infrequent, and in order to eliminate these last faults the intelligent coöperation of many station managers is desirable. In a short time, instructions and apparatus for studying the operation of lightning arresters in service will be ready to send to managers, and conscientious efforts of many will show the rare instances where the arrester fails and will indicate the complete solution of the problem. If the insulation of electrical apparatus has been seriously deteriorated by overheating, a manager should make an effort to ascertain this fact and not befog the problem by laying the fault to the arrester. Furthermore, there is always a necessity for engineering in the choice and location of arresters to give the best conditions of protection.

Up to the present, the design of electrical transmission apparatus and that of protective apparatus have gone hand in hand. For example, when the arrester was adjusted to its maximum permissible sensitiveness and failed to protect the end-turns of a transformer, the transformer designer came to the rescue by adding extra insulation to the end-turns. At present, the designers of protective apparatus are endeavoring to design arresters for each potential, that will limit the rise to 150% of normal. That arresters have been faulty is conceded, but the designer has too often to meet the condition of weak insulation and the occurrence of rare lightning phenomena. The problem is further complicated by the varied demands of protection at different voltages of transmissions.

A brief survey of the relation of line voltage to the problem of protection is herewith given.

Line potential and the problem of protection. As a thunder-cloud approaches a transmission line, each lightning discharge increases the severity of the induced stroke on the line. In this wide range of intensity, it is easy to imagine that there is an average value of potential, due to discharges to the earth within a mile of the line, and yet not actually striking the line, which occurs frequently. Its value is unknown, but, judging from the fact that it does not jump over the insulators, it is less than the spark-potential of the insulator and therefore, in general, less than 200 kilovolts. The indications are, however, that it is probably not less than 100 kilovolts.

The thunder-cloud takes no account of the potential of the line, so that a 500-volt trolley wire will get the same induced lightning stroke as a 60-kilovolt transmission in the same location. 100 kilovolts would be harmless to the insulation of the 60-kilovolt line, but an arrester must operate instantly and rapidly on a low-voltage line to bring this potential down to a safe value before the relatively weak insulation is damaged. On high-potential lines, furthermore, the brush discharge potential of the line conductor is not much above the line potential, so abnormal potentials may lose an appreciable part of their dangerous peak values through the energy thus lost in the atmosphere. There is one compensating condition in the protection of low-voltage systems, in the greater factor of safety in the insulation customarily used in the construction. It is not unusual to find a 2,000-volt transformer with a factor of safety of 5 to 10 and a lightning-arrester with a spark potential of twice normal, whereas a 60-kilovolt transformer may have a factor of safety little greater than two, and the arrester must be adjusted within this limit.

Effect of location of circuits on the problem of protection. There is another compensating condition favoring the design of arresters for low-potential circuits; namely in the shorter lengths and favorable locations, both due to natural engineering requirements. For example, 2300-volt circuits are usually short and confined to the streets of a city where the houses and overhanging trees protect the lines from lightning charges induced by the storm clouds. Trolley wires are often overhung with feeders and have an additional compensation in leaky insulators. The numerous supports of the trolley wire each with a low-insulated, leaky-surfaced insulator help to discharge the static electricity to ground at the point where it is freed. Unfortunately, 2300-volt circuits and trolley lines are not confined to shady avenues and city streets, but are often carried into the open country. This is the part of the circuit which needs special care and protection against cloud lightning. A striking illustration of this necessity was shown last summer at a coast city The city trolley was connected with a beach line. A storm passed over the city, disabling more than a dozen cars on the beach but none of the cars on the city streets. All these cars carried arresters of antiquated design. Another trolley circuit, an interurban, in a lightning storm district passes along miles of road with many large trees on each side. In consequence, with the ordinary protective apparatus, burn-outs of motors from lightning are so infrequent as to cause no disturbing increase in the repair expense.

Factor of damaged insulation. In the matter of satisfactory protection, a factor enters which is beyond the control of the lightning-arrester designer. This is the effect of the abuse of the insulation of electrical apparatus. These abuses are usually confined to overheating and wetting the insulation. Overheating produces a gradual weakening which will finally cause a short-circuit even at normal voltages. This final catastrophy, if due to normal voltages, will not be affected by the presence of the lightning-arrester, but the arrester, according to its efficiency, will lengthen the time during which the insulation can withstand abnormally high potentials.

Guarantees. Because of the necessity for the insertion of a conditional clause stating that the insulation has not deteriorated, no form of useful guarantee that the arrester will protect the insulation can be given by the manufacturer, even when an absolutely perfect and universally applicable lightning-arrester is in commercial service. A guarantee that an arrester will not be destroyed within a given time, say one year of service, could be given, but it would put a premium on making the arrester safe, even at the expense of the apparatus, and is therefore objectionable.

Regarding service tests. The final criterion of success of an arrester is infallible protection under every condition of service. Perfect operation in one location does not prove the success of an arrester unless it can be shown that the lightning in that location was severe and of widely variable nature. There is an element of luck with storm-centers away from the line; specially high factors of safety of insulation, favorable location of lines, and freedom from resonant conditions must be taken into account. A considerable expenditure of money and time must be made before any conclusion can be drawn from a service test The information from a laboratory test, while not final in its conclusions, gives immediate results and brings an earlier solution.

Trouble inspection. Furthermore, the service test alone gives no information regarding improvement of design. If the arrester is destroyed, the designer is often called in to inspect and investigate the cause of the trouble. There are perhaps a few pieces of fused metal, arc holes, broken chunks of porcelain, burned insulation of the leads, and a disgruntled manager. The results are visible. The cause of the trouble disappeared as rapidly as the air vibration of explanation. One goes over a series of possible causes like the presence of bugs, bad condition of the arrester due to previous operation and lack of inspection, collection of dirt on the bushings, grounded phase, direct stroke, line-to-line surge or line-to-ground surge, standing wave, and faulty design. On the other hand, if the failure of the arrester was the failure to protect the apparatus, speculations are made on the nature of the stroke of lightning, its natural frequency, duration, quantity of electricity, standing wave, and resonance. If the puncture was internal, there is sometimes the question of abnormally weak insulation due to poor workmanship, or abuse in the form of overheating, wetting or mechanical injury. Possibly the arrester was not at fault. If the trouble was a standing wave, it might have been in a poor location to protect. The earth connection may have been bad, and so on.

If the insulation was punctured at the bushing, or the spark jumped through the air, there is seldom a question of damaged insulation and the fault must be laid to the arrester circuit. There are at least four leading questions of interest to the engineer.

1. Subject of quantity and frequency. Was the arrester resistance too high?

2. Subject of frequency. Was the equivalent needle-gap too high at the particular natural frequency of the discharge? (Some arresters vary in equivalent needle-gap with a variation in natural frequency of the lightning surge.)

3. Subject of earth connection. Was the resistance of the earth connection abnormally high, or was the distance between the earth connection and arrester abnormally long?

4. Subject of resonance. Was there a standing wave with a node at or near the arrester and an anti-node or peak at the point of puncture?

The first three subjects are matters of design. The fourth subject is a matter of the location of arrester and choke-coils. Unless the trouble inspector enters the field with predetermined knowledge of the action of an arrester under the strains of different kinds of lightning strokes, the inspection is fruitless. Such a knowledge can be obtained only through laboratory tests with artificial lightning.

Example of interpretation from inspections. As an example of interpretation from an inspection, the following is given. Arresters of special design, set very close to line potential, were installed on a long system operating at 13,000 volts. Near the generating station, the arresters were arranged to give less possibility of short-circuit under heavy lightning than in the substations. During the entire winter the line superintendent conscientiously examined and removed tell-tale papers in the arrester gaps. About the only information gained during all this time was that the arresters were sufficiently sensitive to operate from the internal lightning caused by switching and other accidental disturbances. A short time ago a lightning storm occurred. The tell-tale papers at one sub-station showed discharges through the arrester. At another sub-station two current transformers were punctured, but the tell-tale papers in the arresters at the cable terminal house near the sub-station, and in the arresters in the sub-station itself, showed no discharge. In other words, the discharge passed two sets of lightning-arresters adjusted close to normal line potential and punctured the two transformers. Why did the arresters fail? What kind of lightning stroke was it?

To answer these questions, the predetermined fact is known that these arresters are not sensitive to the first half-cycle of the lightning discharge and therefore not sensitive to low-frequency high-potential surges. When these arresters were installed, the designer knew nothing of the fact nor how to overcome it. It is also known that these arresters are exceedingly sensitive to high-frequency discharges.

A probable explanation is that high-frequency cloud-lightning caused a discharge over the entire arrester, cutting out all resistance. A low-frequency surge followed which passed the other arresters and damaged the current transformers, the weakest insulation in the sub-station. There is one other possible explanation; there may have been a standing wave with the nodes at the arresters. This seems improbable, however, because there were two arresters, and, furthermore, the same phenomenon has been observed in several other cases where the insensibility of this type of arrester to low frequency seems to be the fault.

In another paper, the method of correcting the design of the arrester considered above is given. If a manager of a transmission system assumes the untenable position that the manufacturer has sold a piece of apparatus which will not take care of all lightning conditions and is responsible for replacement of arresters, an embarassing commercial situation arises which cuts off free intercourse between the engineers and consequently impedes progress. Perhaps a manager has decided that the arresters are an unnecessary evil and has taken them all off the system. With good luck, such a system may run several months without trouble from lightning, but each high-potential surge which enters the station will do a definite amount of irreparable damage to such insulation as is not self-repairing. Sooner or later, enough strokes of high potential occur at one point to cause a puncture, and all other points weakened by overstraining are likely to give way under the secondary strains of the energy surges of dynamic potential coming from the initial short-circuit.

Unless the cause of the failure of the arrester can be traced to something specific, little improvement of design is possible. We have already come to the stage where accurate measurement is the life of further progress. It is necessary to produce artificial lightning of varying potential, quantity, frequency, and duration in the laboratory, and to study with it the characteristic behavior of a lightning-arrester. By applying considerable dynamic energy to the arrester at the same time, the secondary effects of dynamic current discharge and the endurance of the arrester may be determined. Knowing the characteristic behavior of an arrester under varying conditions, it is often possible to make a very plausible surmise of the nature of the cause of the failure. The engineer who advances the argument, as has been done, that " it is only a laboratory test and does not prove the value of the arrester " loses the proper viewpoint. The object of the laboratory test, aside from the educational experience it gives, is to prove the converse condition regarding an arrester; that is to say, if the arrester will not withstand reasonable laboratory tests in conjunction with the insulation which it is designed to protect, it is sure to fail sooner or later on the line. If the laboratory test shows the arrester weak in some particular point, and that point only, it does not necessarily condemn the arrester, for it may be due to a condition which may be taken care of by some other kind of arrester or one that may not occur on the circuit in years. But, if such an arrester fails, it often seems permissible to attribute the cause to this weakness. With such knowledge, it is possible to employ to great advantage a particular type of arrester on certain kinds of circuits or in certain locations.

An analysis preliminary to standardization recommendations. Before attempting to write standardization rules, it is pertinent to review the necessities of the situation.

First of all is the selection of names for the apparatus and the general terminology as a means of common intercourse.

The second consideration is the nature of the lightning so far as known, and the strain which must be relieved by the protective apparatus.

The third consideration is the nature and characteristics of the insulation to be protected.

The fourth consideration is the characteristics of the protective apparatus.

The fifth consideration is the nature of the test with artificial lightning, which will demonstrate the characteristics of the protective apparatus.

1. TERMINOLOGY

Lightning. Lightning is a general term to express surges of potential anywhere of dangerously abnormal value. The subdivisions of lightning are external and internal. Cloud lightning is external lightning. Dangerous surges due to switching, etc., are internal lightning.

Protective apparatus. There is required a general term to cover all devices which give protection. Protective apparatus is suggestive, clear, and brief.

Lightning-arresters. A name is required for devices connected not only between lines but also between lines and ground. So far, " lightning-arresters " is the commonly used term, and it seems desirable to retain this to avoid confusion.

Internal-surge protectors. Another device, which may be of the same form as a lightning-arrester, is connected only between line and line, not to ground directly. There are a great many of these devices installed at the present time, and it is desirable to have a convenient special term to distinguish them from lightning-arresters. The term "static protector" has been frequently used. The term is not suggestive of the nature of the device, and may be confused with the apparatus known for a long time as a "static discharger." "Static" means specifically the displacement in a dielectric medium. There are static strains which may be distinguished from one another. There is the normal static strain of potential between line and line, which varies every instant with the wave of electromotive force of the generator. There is also the excessive static strain between line and ground due to cloud-lightning strokes. There is, still further, the excessive static strain between line and line, due to the stoppage of a dynamic flow of electricity in a number of ways; and there is, finally, the excessive static strain between line and ground, due to the gradually accumulated static electricity from wind, rain, etc., coming in contact with the transmission line. This last form of static will not be released at all by the static protector, so there seems to be no reason for standardizing this false nomenclature. Devices for carrying off the gradually accumulated static usually have low current-carrying strength and have been known for years as "static dischargers." Since this form of static is directly generated in the line and the word "static" is suggestive of rest, it seems desirable to retain this term "static discharger" for the discharges of gradually accumulated static electricity. Conversely, since the other static stresses are indirectly generated from electromagnetic stresses, and, furthermore, since this electrostatic stress is continually being transformed into electromagnetic stress and back again in the form of surges, it seems desirable to adopt a term like "internal-surge protector." It lacks brevity but there is no doubt of its meaning.

A lightning-arrester is always more or less of an internal surge protector according to its design, and it may have auxiliary devices which make a static discharger of it also. On the other hand, an operator should not deceive himself into a sense of security because a static discharger has been sold to him under the misnomer of a lightning-arrester. Again, an operator cannot expect an internal-surge protector to protect against surges of an external origin, as, for example, cloud-lightning.

Earths (*connections, resistances, etc*). The word "earths" is used here specifically to mean the connection between the conductor and the earth in which it is buried. On overhead lines, it is usually the only "ground" connection. (See below, "*Grounds.*")

Length of the earth connection of an arrester is the distance from the arrester to the conducting stratum of the earth.

The earth resistance of a lightning-arrester is the ohmic resistance from the arrester to the conducting stratum of earth. Its value may be obtained by measurement between three earthed conductors.

Grounds. "Grounds" is a more general term than earths. A phase may become grounded without being earthed; for example, a cable having its armor insulated from the earth may become "grounded" by having one of its conductors connected with the armor. The armor may be "earthed" by connecting it with a conductor buried in conducting earth; in this case, we may still speak of the phase as grounded. If the transmission system is a mixed cable and overhead system, "earthing" the armor may make a considerable change in the surges through the system.

Sparks. An electric spark is the phenomenon of conduction of electricity by a luminous gas.

Arc. An arc is the phenomenon of conduction of electricity by the heated vapor or vapors of the electrode.

Dielectric-spark lag. Is the time elapsing between the application of the sparking potential and the complete formation of a spark.

Natural or proper frequency of a circuit is the number of oscillations per second of potential or current which will take place if the circuit is allowed to discharge without interference from excessive damping or extraneous power. Such a circuit involves the presence of both capacity and inductance.

Continuous and continual, as applied to the electrical terms, retain their defined sense. A continuous oscillation is one which appears without a break. Continual oscillations are successive sets of oscillations with more or less interval between the sets. A generator furnishes continuous alternations, a Tesla transformer produces continual oscillations. Continuous lightning is sometimes produced by one phase of a generator when another phase is short-circuited. Continual lightning is produced on a non-grounded neutral system when one phase is connected to ground through an arc. Both continuous and continual lightning may be temporary, but should be distinguished from transitory lightning.

Recurrent surges is a term synonymous with continual surges.

Surges. Electrical surges is a term having a sense a little more general than lightning. Any unusual rush of current or potential is a surge. If the surge potential reaches a dangerous value, it is lightning.

Transitory. Transitory, as applied to electrical terms, retains its defined sense. Cloud-lightning gives transitory lightning on a transmission line. Many lightning-arresters are designed for transitory lightning but not for continual lightning.

Equivalent spark-gap. This is a general term to express the puncture-potential equivalent of a piece of apparatus or insulation. The gap is in parallel with the device and of such value as to cause at least 90% of the spark discharges to pass through the device, and not more than 10% across the gap. The equivalent spark-gap is the only means of directly indicating the potential of a transitory charge. The specific terms are equivalent needle-gap and equivalent sphere-gap.

Equivalent needle-gap. Is the gap of the value explained above when the electrodes of the gap are needles.

Equivalent sphere-gap. Is the gap of the value explained above when the electrodes are spheres. It is necessary to state the diameter of the spheres; for example, equivalent 2-inch sphere-gap.

Equivalent spark-gap characteristic curve. This is the relation of the applied potentials as represented by gap-lengths (abscissas) to the equivalent spark-gap (ordinates). In this expression, the specific words " needle " or " sphere " may be substituted for " spark."

Dynamic. Used as an adjective to the words current, voltage, wattage, energy, etc., designates the current, voltage etc., which come directly from the dynamos or generators, as distinguished from the current, voltage, etc., which come from static charges, electromagnetism, cloud-lightning, etc. on a line. The latter is of relatively small energy. There is no general term to express all the discharges that are not dynamic. "Static" is a word used in this sense a number of times, " lightning " is another; but they are both specific and not general. For example, the internal lightning from one phase of a generator when another phase is short-circuited is really dynamic potential, dynamic current, dynamic energy, etc. It is true that before a discharge takes place there is always a storage of energy in the static stress, in spite of the fact that the source of this static stress may have been due to the aforementioned condition, or to the sudden interruption of a dynamic current, and, therefore, static comes the nearest to expressing the general sense. Non-dynamic would be a general adjective covering the phenomena not directly derived from the generator.

Static. This term was originally applied to the stationary charges of electricity on rubbed glass, wax, etc. The use of the term has been extended until it covers all forms of electric displacement in a dielectric. This electric displacement may be changing its value at every instant, and the electric charge is therefore not stationary. The variation in dielectric displacement gives the static current or condenser current.

Non-dynamic. Is an adjective applied to the electrical terms to cover all effects which do not have their source directly in the generators.

Accumulated static charge. This term applies to the charges of electricity which accumulate on a transmission line due to wind, rain, etc. and represents an electric displacement in the dielectric between line and earth.

End-gap static. Discharges of a multigap arrester. On high-potential circuits, a few of the series gaps at each line connection are bridged by tiny sparks which give out a buzzing sound. The number of gaps bridged by the sparks depends on several factors—applied potential, relative capacity of each cylinder to its adjacent cylinder and ground, and leakage through or over the surface of the supporting porcelain.

Grounded neutral system, and *non-grounded neutral system* as applied to a transmission circuit are terms which are self-explanatory. A three-phase delta circuit may have an artificial neutral made by the connection of auxiliary apparatus in *Y* relation, and this neutral may be grounded. The word neutral cannot be omitted in this expression without confusion with the continual lightning condition of an accidentally grounded phase.

Forced oscillations. Forced electrical oscillations are oscillations impressed on a circuit regardless of the free, natural, or proper oscillations of the circuit. Alternations from a generator on a line are forced alternations.

Resonance. If the forced oscillations have the same frequency as the natural oscillations of the circuit there is perfect resonance, or tuning, and both the current and potential will assume abnormal values.

Standing wave. A standing wave is to be distinguished from a traveling wave. A standing wave is caused by traveling waves moving in opposite directions and so timed that they pass each other always in the same relative position. The result will be nodes at certain points and anti-nodes at points midway between. The nodes remain at zero or normal potential, and the anti-nodes vary in potential from double the potential of a single wave in the positive sense to the same potential value in the negative sense.

Rate of discharge is the current, $I = \frac{dQ}{dt}$. The rate of discharge is an important factor in connection with the resistance of a lightning-arrester.

Acceleration of discharge. Is the rate of change of current. Acceleration $= \frac{dI}{dt} = \frac{d^2Q}{dt^2} = \frac{E}{L}$. The acceleration of discharge is an important factor in connection with the inductance of a lightning-arrester circuit.

Recurrence. Recurrence is a convenient word to use to avoid confusion with the word frequency in a technical sense. The frequency (natural) of lightning may be about a million cycles per second, but the frequency of recurrence of lightning stroke may be expressed in minutes or months.

Oscillogram. The tracings of wave-forms taken with an oscillograph.

Multigap. Multigap expresses the condition of a number of gaps between conductors in series.

Multipath. Multipath expresses the condition of a number of gaps or circuits in parallel.

Multiplex connection. On a lightning-arrester, this commercial term means that there are certain cross-connections between phases of the arrester above the earth connection. These cross-connections may or may not have an appreciable resistance.

No-gap aluminum arrester. An aluminum arrester composed of a series of aluminum electrolytic cells connected directly to the lines without the intervention of any gaps.

Gap aluminum arrester. Is the same as above except there is a gap between each phase wire and the cells to prevent the natural capacity current of the cell from flowing continuously.

Graded resistance arrester. A trade term to express the form of multigap arrester according to the 1907 design. A number of resistance circuits of variable ohmic value are thrown in parallel across the simple multigaps. These resistance circuits have a common connection at one end and tap in at different points on the multigaps.

Nature of lightning. In the A. I. E. E. PROCEEDINGS, May, 1906, the writer gave a brief outline of lightning effects as a basis for a laboratory study of methods of measurements. Dr. C. P. Steinmetz has given a very complete classification of lightning on transmission lines* from the broad standpoint of the analyst of the phenomena. While it is necessary to keep in mind the classification according to the phenomena, it is more direct for the designer of protective apparatus to analyze according to the effect of the lightning on the insulation and the lightning-arresters. Regardless of the cause of the lightning, the arrester and insulation take into account in the two kinds of lightning, transitory and continual, only the three factors—the frequency, the duration, and the potential of the stroke.

The nature of lightning on electrical transmission has been very little studied by direct measurements, on account of the lack of specific instruments with which to make the measurements, the erratic appearance, the transitory duration, and the danger involved.

Frequency. By a study of artificial lightning, it can be demonstrated that a transmission line may be subjected to any frequency of electrical oscillation ranging from one-half cycle per hour (gradually accumulated static electricity) to about a billion cycles per second. On many particular lines, the frequencies of oscillations will exist probably in groups of harmonics. The first and lowest group starts with the generator frequency and runs up in odd multiples thereof to all the higher harmonics. On account of the impossibility of getting very abrupt changes of magnetism in a generator (due to the relative permeability of iron and air) the upper harmonics from the generator wave very quickly become negligible.

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*PROCEEDINGS of A. I. E. E., March 1907.

It is usual to assume that the fundamental wave of the generator will not attain an abnormally dangerous value on account of the limitation of the exciter voltage, but, under the special condition of a short-circuited phase on a multiphase generator, the voltage of the phases not short-circuited may rise to a very dangerous value. Several years ago Mr. L. Robinson, at the suggestion of Dr. C. P. Steinmetz, took oscillograms of this condition of operation in some large generators and found a rise of 250%. This surge requires special attention in the application of lightning-arresters.

The second group of oscillations starts with the natural period of the electrical circuit, including in its factors the inductance and capacity (static) of transformers, cables, overhead lines, choke-coils, and translating devices of any kind in the common circuit. There are also the upper harmonics of this group. The first group may overlap the second group. If any frequency of the first group coincides with that of the second group, then that particular oscillation of the second group is in resonance (or in tune) with the particular wave of the first group, and its free oscillation will be magnified until the natural energy losses of the oscillation are equal to the energy derived from the harmonic of the generator wave.

The third group of oscillations includes those starting with the fundamental frequency of the transmission line or cable (not including the apparatus.) The line or cable may oscillate as one segment or any odd multiple thereof, giving thereby all the upper harmonics.

The fourth group of oscillations may be designated as miscellaneous. In this group are such oscillations as those between the system and an isolated conductor. An example of this kind of oscillation is found in the multigap arrester. Usually, about a half-dozen gaps next to the line connection will have a spark-discharge across them continually. Each time the second cylinder is connected to the first, an oscillation is set up on the line, the results of which have been experimentally measured.

The fifth group of oscillations comes from external sources and will oscillate independently of the line. In this group are the forced oscillations on the line derived from cloud-lightning.

The natural frequency of cloud-lightning, not yet having been measured, is presumably determined by the static capacity of the part of the cloud that is discharged and the inductance of the discharge path between cloud and earth. Since both the inductance and capacity vary, the natural frequency of the cloud-lightning will also vary over a limited range. In this group come also the oscillations on a line from wireless telegraphic signals and induction from adjacent transmission lines. If any of the oscillations of the previous groups are in tune or resonance with one of the fifth group, then such an oscillation may be enormously magnified. It is useless to speculate on whether or not cloud-lightning has any upper harmonics.

Following is a summary of the five groups.

First group. Generator frequency and harmonics.

Second group. Natural frequency of the main circuit and harmonics.

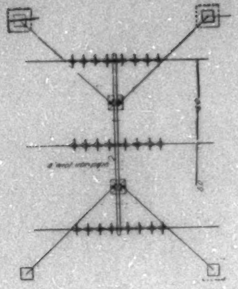
Third group. Natural frequency of the line circuit and harmonics.

Fourth group. Miscellaneous oscillations.

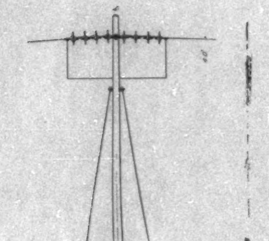
Fifth Group. Forced oscillations from an external source.

Comments on the five groups. The generator and cloud-lightning are both sources of energy. The generator frequency is below any of the natural periods of the lines and therefore its fundamental wave is impressed on the line from end to end with only relatively slight modifications of form by inductance and capacity; the cloud-lightning frequency is unknown, but there is reason to believe that it may be of the order of 100,000 to 1,000,000 and consequently agrees with some of the possible oscillations of the other groups. The oscillations on a line due to cloud-lightning are of a double nature; there are, first, the forced oscillations due to the natural frequency of the cloud discharge, and, secondly, the free oscillations of the charge left on the line.

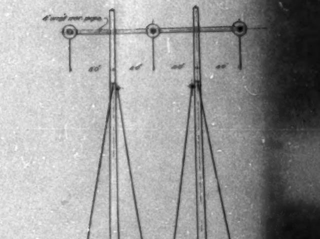
1. These forced oscillations may be more or less magnified or nullified by interference. Unlike the generator forced wave, the cloud-lightning forced wave may be far above the natural frequency of the line, and the whole line cannot rise and fall simultaneously with the cloud-lightning oscillations. There will be a succession of waves which will be partly reflected from the ends of the lines, and the reflected wave traveling in the opposite direction will combine algebraically with the waves it meets. If the line is an odd multiple of


4" wrot. iron pipe

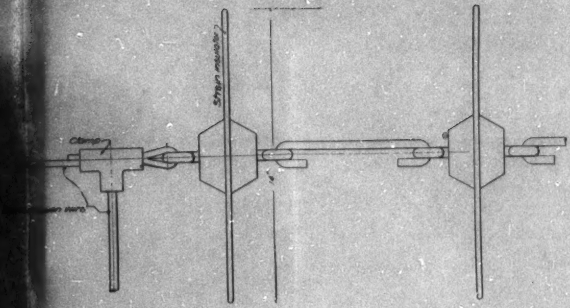
Plan



Side Elevation


4" wrot. iron pipe
60'
60'
60'
60'
Reinforced Concrete pole

Front Elevation


Clamp
Strain insulator
wire

a quarter wave-length, two waves traveling in the opposite direction will meet at a certain point on the line and will neutralize each other; the succeeding wave will do the same at the same point; consequently this point of the line will remain at constant potential. At a quarter wave-length in either direction on the line, the potential is changing its value at every instant as the waves cross each other. The result is that the potential will vary gradually and harmonically from zero to twice the original height of the traveling wave. This effect has been called a standing wave. It is variable in value of potential at every instant, but is fixed in its position on the line. Three positions of such a wave are illustrated in Fig. 1. *A* and *B* are two points on the transmission line. The dotted curve represents the reflected wave, and the broken curve the standing wave. The point *A* is zero for all positions of the waves and is therefore the node. The point *B* is zero in the top curves, 150% in the middle curves, and 200% of the traveling wave in the lower curve.

If the length of the line is not an odd multiple of the quarter wave-length, then the reflected waves cause a jumble without definite form.

If the induction from the clouds is electromagnetic (horizontal lightning stroke parallel to the line), there is no resultant quantity of electricity on the line and the surges set up will die out gradually by loss of the initially imparted energy; but, if the induction from the cloud is electrostatic, there will be a definite charge of electricity set free and left on the line.

2. The free oscillation. When a thunder-cloud over a line discharges, it may set free a charge distributed over the line according to the area of the liberated charge on the cloud and its position relative to the line. The length of charged line may be perhaps of the order of 1000 ft. to 5000 ft. If the line had sufficiently high resistance, this charge, when liberated, would spread over the line as a bucket of water flows when thrown into an empty trough. The line resistance in reality is almost negligible, consequently the energy of the charge will be transformed into electromagnetic energy and back, continuing to oscillate until the waves are damped out. Neglecting leakage to ground, this charge will finally have changed its position from the occupancy of the capacity of a short length of the line, to the occupancy of the total capacity of the line, and in consequence its potential will have decreased proportionally. Mean-

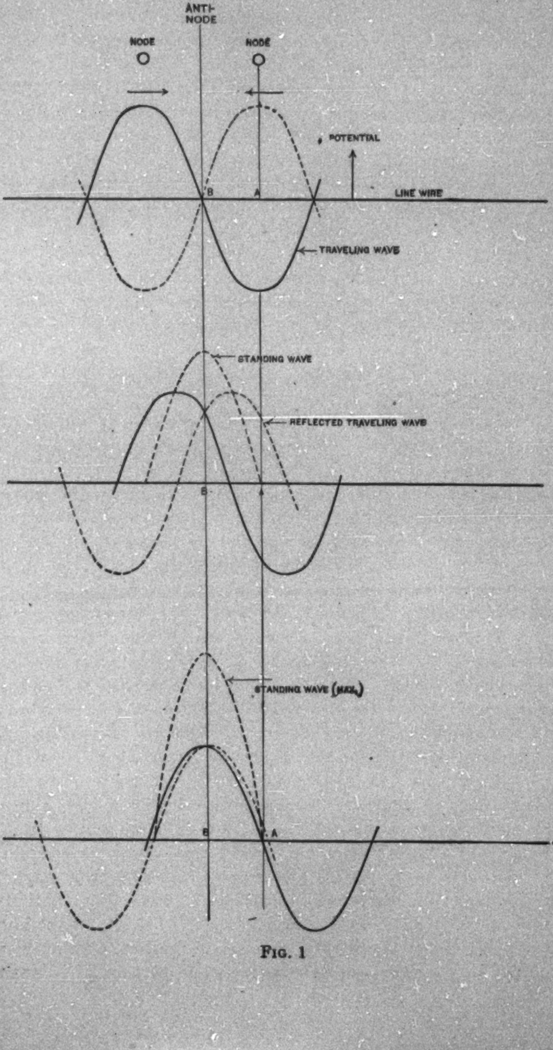

ANTI-NODE
NODE
NODE
POTENTIAL
LINE WIRE
B
A
TRAVELING WAVE
STANDING WAVE
REFLECTED TRAVELING WAVE
B
A
STANDING WAVE (MAX.)
B
A

FIG. 1

while, the waves have traveled in both directions on the line, giving the possibility of a standing wave.

We can examine the condition giving a standing wave by assuming a fictitious line 100,000 ft. long and the length of the line covered by the induced charge at 2000 ft. The quarter wave-length then is 1000 ft. If the line is divided into imaginary 1000-ft. sections, and, if the liberated charge should so occur as to cover exactly two of these sections, the reflected waves would be so timed as to cause standing waves. If the charge were liberated in any fractional position of the 1000-ft. section, the standing wave would be more or less destroyed.

Following out this line of reasoning, it is evident that a standing wave is a matter of chance not only in the relative location of the liberated charge on the line, but also in the relative length of the charge to the length of the line. If this theory is true, strokes of equal potential may vary greatly in their resultant effects.

There is an important condition of surge, involving probably all the first three groups mentioned above. This has been mentioned elsewhere as the grounded-phase condition. In this, the generator is the source of energy, but it does not force the oscillation into the system. Owing to the grounded-phase condition of capacity, the generator produces a static charge which is set free to vibrate by the making and breaking of the arc between the faulty phase and ground. The phenomenon is somewhat analogous to putting a spring under tension and suddenly releasing it. As with the spring, the electrical oscillations die out, but may be renewed a number of times during a half-cycle of the generating wave. An oscillogram of this condition is shown in Figs. *P*, *S*, and *T*, "Methods of Testing Protective Apparatus," PROCEEDINGS, American Institute of Electrical Engineers, May, 1906.

Duration of lightning. Nearly all lightning oscillations are individually of short duration. There is one notable exception; namely, the continuous surges set up on one line from a parallel line (*e. g.*, telephone circuit under a power circuit). All the transitory surges have a logarithmic decrement of potential and current. The rate of decrease of the peaks of the lightning potential depends upon well-known laws; it is proportional to the rate of dissipation of the energy of the stroke. The energy of this electrical charge is dissipated in at least three ways; radiation, heat, and chemical transformations.

Hertz has shown that an open circuit is a good radiator of energy (wireless telegraphic waves) and therefore a poor oscillator. On the contrary, a closed circuit is a poor radiator, but it will oscillate for probably several hundred cycles, provided the energy is not absorbed in resistance and arcs in the circuit. Hertzian waves are radiated only at extremely high frequencies. Lower frequencies radiate in the form of brush discharge only There is an analogy to the hertzian waves in sound vibration. If the air is not struck with a quick blow, it slips around the vibrating material and does not send out a sound wave. A transmission circuit may oscillate as either a closed circuit or an open circuit. Line-to-line oscillations are examples of the former; line-to-ground oscillations of the latter.

The line wires, as closed circuit oscillators, have a very low ohmic resistance and therefore, as far as this factor is concerned, a small decrement of voltage. If the oscillation is low enough in frequency to pass through transformers, the hysteresis and eddy losses in the iron will very quickly destroy the free oscillations. In each of these cases the energy of the electrical discharge is transformed into heat.

In arcs, especially the liquid-electrode types, and when the oscillating current is passed through electrolytes, such as the aluminum-cell type, more or less energy is absorbed in chemical dissociation.

Decrement. What is the best value of decrement? This question is open to discussion. The shorter the duration of the oscillation, the less will be the liability of damage to the insulation; or the quicker the lightning-arrester operates after the potential rises, the less the likelihood of damage to the insulation.

Without going into mathematical refinements, the duration of lightning, as affected by logarithmic decrement, can be demonstrated by simple curves. The subject of oscillating current is thoroughly treated in a number of text-books, but there are certain specific conditions concerning lightning which make some of the general statements regarding the surges inapplicable to lightning on transmission lines. As an example, the general statement is made that with a fixed inductance, capacity, and quantity of electricity, the time of quickest discharge exists when the value of resistance in series is equal to the critical value $R = \sqrt{\frac{4L}{C}}$. This is not true for lightning on a transmission line without lightning-arresters, and it is further from the truth for the lightning-arrester circuit itself. The duration of lightning on a transmission line without arresters will be shorter if the resistance (or its equivalent in other energy-absorbing power, as brush-discharge, electrochemical energy, etc.) is less than the critical value. The arrester is placed directly in shunt with the transmission apparatus, and, although the surges on the line may continue for a longer time with negligible resistance in the arrester, the potential across the arrester is reduced quickly to a safe value in spite of the longer duration of current. The duration of lightning is the time required for the potential to reduce to the safe value. The relations are shown graphically in Figs 2, 3, and 4. Fig. 2 shows two curves of a potential discharge when the only variable is the initial lightning potential. The resistance has a value above the critical value. The higher the initial lightning potential in this case, the longer will be the duration of the lightning. This corresponds to the discharge of lightning through an arrester or static discharger containing high series resistance.

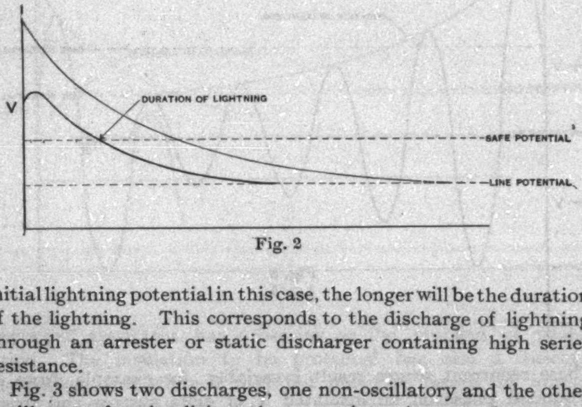


Fig. 2

Fig. 3 shows two discharges, one non-oscillatory and the other oscillatory; for simplicity, these are given the same decrement. The resistance in the case of the oscillatory discharge is less than the critical value, and the duration of lightning is about the same as for the value of resistance above the critical value.

Fig. 4 shows the condition of most rapid discharge of lightning. The resistance lies between the two values of Fig. 3, but the rate of energy-loss is greater. The second half-cycle brings the potential to the safe value. If the energy is absorbed in electrochemical action, as in the aluminum cell, the energy loss is proportional to the quantity of electricity, and the resistance may be zero without affecting the result. Furthermore, the critical lightning potential of the aluminum and liquid-electrode arresters will prevent the potential from rising above the safe value on the first half-wave. To obtain the same result at the multigap arrester terminals, it must be possible to cut out all series resistance if the viciousness of the discharge demands it. The above discussion is made without reference to the dielectric spark-lag.

Continual lightning. Recurrent surges. Although each lightning surge is transient, in general there may be a succession of free oscillations with normal value of potential between them.

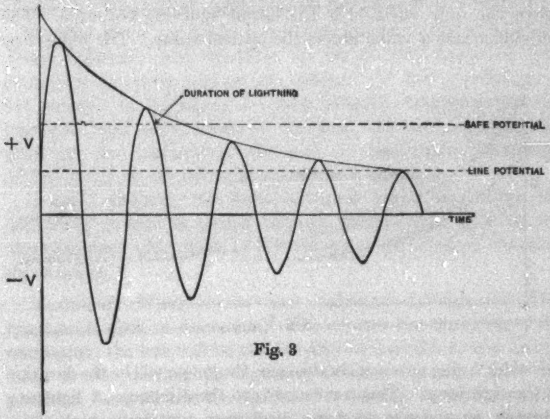


Fig. 3

These recurrent surges result invariably; for example, from a grounded phase on an insulated Y or delta system and from a loose contact on an alternating-current trolley system. As a rule, the duration of each surge cannot even be guessed, but the total duration of the successive surges is limited only by the removal of the condition which caused them.

Potential of the surge. This subject is best treated under the two heads of transitory oscillations and continuous oscillations.

In the case of free or natural oscillations, there is always a loss of energy and a consequent decrement in the successive peaks of potential. The only method of measuring potential in this case is by the equivalent spark-gap. If the oscillations are sufficiently low so that a quarter-cycle is not greater than the dielectric spark-lag of the gap, the gap may be expected to be proportional to the potential. On the other hand, if the frequency is exceedingly high, or the drop of potential is rapid, then the gap will no longer measure the peak value of potential, but some lesser value of potential depending on the two factors, spark-lag and logarithmic decrement of discharge. An illustration of this was given in a paper by the writer, (Proceedings of the American Institute of Electrical Engineers, May, 1906.) As a result of this condition, the maximum potential cannot be determined and the nearest expression is to state the equivalent spark-gap. This dielectric spark-lag, with some types of apparatus, has a bearing on the problem of protection. The insulation to be protected has also a dielectric spark-lag, and, while it may not puncture before the arrester releases the strain, it may nevertheless receive an injurious blow. If the insulation has the property of "self-repairing" the injury is transient.

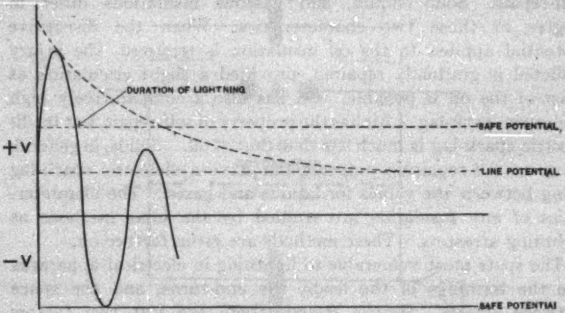


Fig. 4

Continuous oscillations must be distinguished from recurrent oscillations. The needle-gap in parallel will apparently measure the potential in this case, but, continuous oscillations occur very seldom in lightning-arrester work. If recurrent surges follow each other in very rapid succession, it seems reasonable to assume that the equivalent needle-gap is a close measure of the potential, but this condition of "very rapid succession " is too indefinite to be relied upon. In consequence we shall necessarily be limited in this case also to expressing the potential, not in volts, but in equivalent spark-gap.

Nature and characteristics of the insulation to be protected. Tests of dielectric strength have been made for years on insulations with continuously applied potentials, applications ranging in time from one second up. Much of this information is available in published form. Tests of insulation with transiently applied potentials are meager.

Under transiently applied potentials the three types of insulation—solid, liquid, and gaseous—have properties not shown by the tests of continuously applied potential. This difference results from both the dielectric spark-lag and the property of self-repair. Solid, liquid, and gaseous insulations differ in degree in these two characteristics. When the disruptive potential applied to the oil insulation is removed, the injury inflicted is gradually repaired, provided a slight circulation at least of the oil is possible. Oil has also a comparatively high dielectric spark-lag. Air has the property of self-repair, but its dielectric spark-lag is much less than that of oil. Solids, in general, have no self-repairing property but have a dielectric spark-lag lying between the values for liquids and gases. The characteristics of any insulation are studied by the same methods as lightning-arresters. These methods are given farther on.

The spots most vulnerable to lightning in electrical apparatus are the bushings of the leads, the end-turns, and the space between phases. Briefly stated, there are just two factors concerning lightning and insulation that should be known; namely, the potential, and the duration of its application at abnormal values.

4. *Characteristics of lightning-arresters.* After what has preceded, the qualities which an arrester must possess to protect insulation are fairly evident. The questions to be answered are:

A. Is the equivalent needle-gap affected by the natural frequency of the oscillation?

B. By the rate and acceleration of discharge?

C. By the quantity of discharge?

D. What is the nature of the dynamic current suppressing device?

E. What is the endurance $\begin{cases}\text{to single strokes?}\\ \text{to recurrent surges?}\end{cases}$

F. Is there a dielectric spark-lag?

Before attempting to answer these questions by the designation of tests, a review is made of the simpler tests described by the writer in the PROCEEDINGS of the American Institute of Electrical Engineers, May, 1906. To these tests some additions have been made.

First test. Test of static discharger. This test is of less importance than those following. The source of energy, in Fig. 5, is a static machine. The equivalent spark-gap is the value of the gap *G* which causes the discharge to pass through the arrester. The spark-gap is necessarily a sphere-gap because the needle-gap will carry off the current of a small static machine in brush-discharge as rapidly as it is generated, and thus limit the potential to a small value. The condensers are sometimes used as a convenience in observing the spark-distance. The report from the condenser-discharge cannot be confused with any brush-discharge.

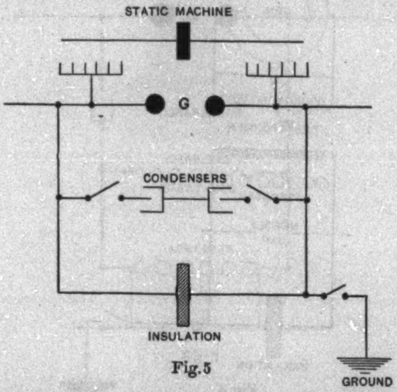


Fig. 5

If the static-discharge has a high frequency, the measurement of the ohmic resistance will permit a calculation of the current flow at double the normal potential of the system. Double potential is here chosen, as in other similar cases to follow, with a specific object in view. For the present at least, it seems necessary to design the insulation of electrical apparatus with a minimum factor of safety of 2. Therefore, 200% gives the discharge current at the limiting value of potential. There is a more important reason for choosing 200% potential for the calculations. Some types of arresters, especially the electrolytic types, have a small current discharge at normal potentials, but have a critical value of limiting potential above which the current flows freely. Choosing 200% normal potential for the purpose of calculation brings out the desirable characteristics of these arresters.

Second test. Equivalent needle-gap at commercial frequency by step-up transformer. Fig. 6 shows the recommended connections of the transformer, arrester, and needle-gap. The presence of

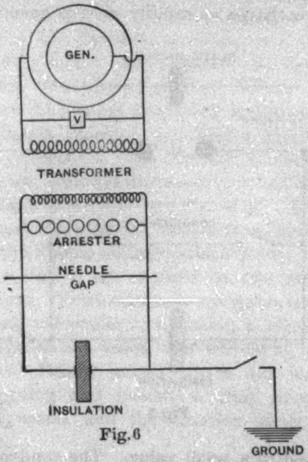


Fig. 6

nsulation is not necessary, although it is sometimes desirable. The thickness and nature of the insulation, when used, is the same as the arrester is designed to protect.

Two equivalent needle-gaps differing somewhat in value are obtained from this test. They are:

a. Equivalent needle-gap (e.n.-g.) by transformation.
b. Equivalent needle-gap (e.n.-g.) by needle-gap.

The equivalent needle-gap by transformation gives the potential of the fundamental wave, and the value by needle-gap gives approximately the peak of the superposed surges derived from the various local oscillations of the high-potential circuit.

There are three tests to be made, making six equivalent needle-gaps in all.

First condition, no grounded phase; switch S open.

Second condition, grounded phase; switch S closed.

Third condition, arcing ground; switch S arcing to maximum length of arc.

Third test. Disruptive-stroke test. There are two simple forms of circuits which are recommended for this test. The principal difference between the two, lies in the use of a static machine as a source of potential in one case and a transformer in the other; see Figs. 7 and 8.

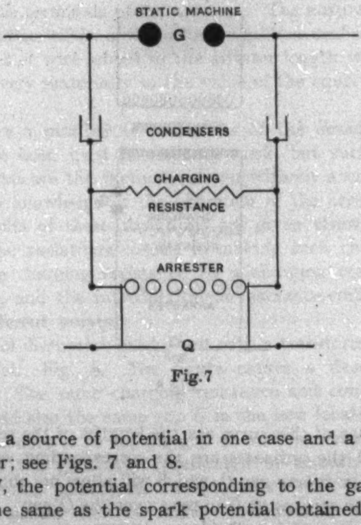


Fig. 7

In Fig. 7, the potential corresponding to the gap G is apparently the same as the spark potential obtained from tests with a transformer, and not the values corresponding to the direct-current potential.

Fig. 8 is a modification of the circuit used by Mr. Percy Thomas a number of years ago for starting the dynamic current across the arresters. The modification results from the different desideratum. The quantity sought is the equivalent spark-gap. It was found that the two gaps, corresponding to the gap G and insulating the arrester from the transformer until the spark jumped both gaps, caused variations in the equivalent spark-gap according to the relative lengths of the two gaps. Some details of the tests which led to the adoption of this simpler circuit (Fig. 8) are given elsewhere in this paper.

Method of disruptive stroke test with the static machine as source, Fig. 7.

Choose a charging resistance of the order of a megohm and state its value if known.

Before connecting the arrester to the circuit, make the equivalent spark-gap characteristic-curve of the charging resistance. This curve shows the limitations of the testing apparatus.

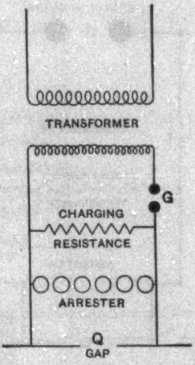


Fig. 8

The abscissas of this curve are the lengths of the setting of the gap *G*, and the ordinates are the corresponding values of the needle-gap or sphere-gap *Q*, which will allow not more than one in ten of the strokes at *G* to pass over the *Q* gap. This curve, once made, is good for all subsequent tests.

Place the arrester in position, and take the equivalent spark-gap-characteristic-curve in the same way as for the charging resistance.

The value of capacity to use in this test need not be standardized. There is a certain minimum value of capacity which gives a discharge of sufficient energy to puncture the insulation which the arrester was designed to protect. The maximum value of capacity which may be used is determined entirely by the size of the static machine. When the leakage through the condenser equals the current generated by the static machine, it becomes impossible to raise the potential across the gap *G* to the spark value. For most of the tests, the writer has found four one-gallon Leyden jars (two on each side) sufficient, and an upper limit of the gap *G* of 5 to 7 in. This apparatus will send a spark over about 200 of the 1/32 in. multigaps under the usual conditions of installation, and the number of multigaps may be greatly increased by using antennae wires near the row of gaps.

The terminals of the spark-gap *Q* should invariably be connected to the terminals of the arrester. The natural frequency of the oscillation will be of the order of a million, and consequently a few inches of wire added to the arrester length will, in many cases, add very materially to the value of the equivalent spark-gap.

There are a number of variations of the circuit of Fig. 7 which have been used in research work, but such variations would complicate the methods of test without a corresponding gain in the knowledge of the operation of the arrester. Some of the results of these variations are given elsewhere by the writer. The variations consist in making such changes as replacing the charging resistance by a charging reactance of a high value, and the introduction of reactance-coils in the circuit at different points.

Method of disruptive-stroke test with a transformer as source of potential. Fig. 8. The figure makes a description unnecessary. The same charging resistance and condensers may be used, and also the same gap *G* in the new location.

The procedure is to set the gap *G*, and then increase the excitation of the generator (preferably of smooth wave-form) until *G* sparks and opens an automatic circuit-breaker. The excitation should then be slightly increased to overcome the effect of the dielectric spark-lag which gives a gradual breakdown of the air in the gaps when the voltage barely reaches the spark voltage. The excitation-circuit, resistance, and voltage are then held constant. The excitation-switch is then opened until the circuit-breaker is closed and then closed again—and so on for each discharge.

The equivalent spark-gap-characteristic-curve is made in this case as in the preceding one. The other precautions are the same.

The upper limit of the capacity of the condensers which may be used, is determined solely by the size of the generating apparatus. The capacity of the condensers should be stated in the report.

The two methods using the same condensers, charging resistance, and values of *G* gap give somewhat different values of equivalent spark-gap. The method of Fig. 5, using the transformers, gives the higher value. A plausible explanation of this may be found in the ionization of the needle-gap by the applied potential previous to the passage of the spark across the gap *G*. This does not occur in the circuit shown in Fig. 7. Since the spark at the gap *G* (Fig. 8) always takes place at peak values, the gap *Q* is always ionized, whereas in transmission practice the generator potential may be at zero potential when the lightning stroke occurs. This feature is unfavorable to the use of the method of test, but the employment of a transformer with its greater energy capacity and availability will often offset the disadvantage. On the other hand, the equivalent needle-gap

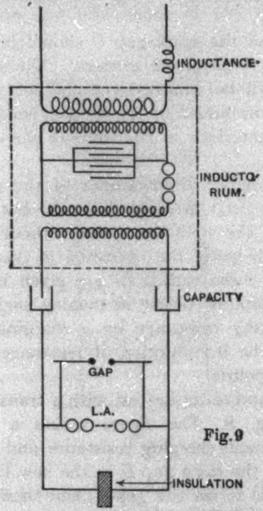


Fig. 9

so found will be at its highest value, since the needle-gap, when it sparks, is ionized to a lightning-potential corresponding to at least two or three times the normal line potential of the arrester. The arrester gaps are also somewhat ionized by the potential.

Fourth test. The Tesla transformer test, Fig. 9.

The natural frequency of this oscillation transformer is usually of the order of 100,000 cycles per second and the continual discharges are good imitations of continual lightning or resonant surges.

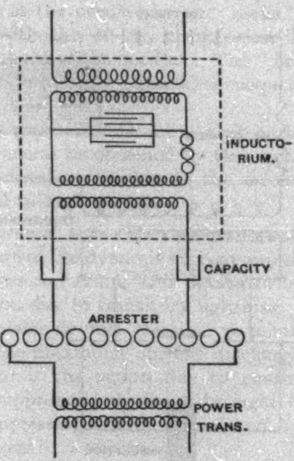


Fig. 10

If it is desired to measure the equivalent sphere-gap by this method, the connections of Fig. 9 seem to be the most desirable. The procedure is to close the switch *S* and then elongate the gap at *G* until the arrester takes all the discharge. A needle-gap cannot very well be used at *G*, on account of the energy lost in brush-discharge from the points.

The Tesla transformer is specially adapted to give the effect of continual lightning. The method of connection to the dynamic circuit is shown in Fig. 10. Condensers are used between the Tesla transformer and the arrester to prevent the short-circuiting of the dynamic-current through the high-potential coil of the transformer. The high frequency passes through these condensers as easily as through a straight wire, but the current at generator frequency is comparatively insignificant. The discharge circuit is arranged so that the current passes in opposite directions, thus lessening the tendency to choose the path through the power transformer. This tendency is still further minimized by connecting the condensers to points on the arrester somewhat away from the ends. These points of connection are determined by trial, the desideratum being to get a uniform continual discharge through the entire arrester.

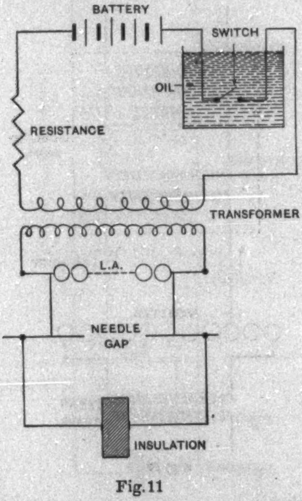


Fig. 11

Fifth test. Half-wave test (Fig. 11). This test for equivalent spark-gap is of great importance as it brings out the sensitiveness of the arrester to the first impulse. An " induction-coil " gives the same kind of discharge in rapid succession and may be used up to the limit of its capacity, instead of the power transformer of Fig. 11. The energy in the induction-coil is limited to a small value, and the observer must assure himself that the energy is sufficient to give the correct value of equivalent spark-gap. The variations of equivalent spark-gap are demonstrated in the tests given in the appendix of this paper, and are made evident by varying the value of direct current in the primary.

In making this test the record should contain statements of the kilowatt capacity of the transformer, the ratio of transformation, and the nature of the primary circuit (battery or dynamo, and the total resistance of the primary circuit). Care should be taken to hold the switch in the primary closed long enough to allow the direct current to rise to its full value.

If a spark occurs at the needle-gap on " make," a flaring arc is formed, which with the 50-kw transformer has sufficient energy to melt the points of the needles. The " break " gives a higher potential and forms only a spark; consequently, it is more convenient to use.

Equivalent spark-gaps of resistances and closed-circuit apparatus cannot in general be obtained by this method, since the presence of such a closed connection on the secondary prevents the rise of potential to high values.

Sixth test. Endurance test. The endurance of an arrester depends on the nature of the dynamic current-suppressing device. There are two factors concerning this device to be determined The first is the action due to transitory lightning. What is the nature of the suppressing device, the time required to suppress the dynamic, and the maximum current discharge?

The second factor is the action due to continual lightning when the current-suppressing device is brought into continual action. Is this suppressing ability diminished by the passage of the dynamic current?

Oscillograms of the current and voltage during discharge will give, with most types of arrester, enough information to make a fair answer to the questions of the previous paragraph. The oscillograms will show:

a. The duration of the dynamic current, and the point of extinction when the instant of starting the current is varied.

b. The voltage across different parts of the arrester.

c. The maximum value of current of the test.

d. If the arrester did not drop the potential of the circuit, a generator of infinite kilowatt capacity could not have done more. If the arrester did drop the potential of the circuit, oscillograms will show where the potential was absorbed, and variations of the current of the test will show the law of relation of current to impressed voltage. From this information the current flow for any size of generator may be determined. If the arrester is designed for transitory lightning only, the endurance is determined by sending discharges at intervals of 10 to 20 seconds until the arrester is seriously damaged or inoperative.

If the arrester is designed for continual lightning, the endurance is determined by sending a continual discharge from some auxiliary device, like the Tesla transformer, over the arrester until serious damage to the arrester or short-circuit to the apparatus results.

An attempt is made below to outline the methods of test which will give answer to the questions at the beginning of the section marked " 4th consideration "

A. Natural frequency. The effect of a variation in the natural frequency of the oscillation on the equivalent needle-gap may be demonstrated, in general, by a comparison of the values obtained from tests numbers 1, 2, 3, and 5. The first test with high-potential direct-current is not always available. Static machines furnish a very small current; the leak over most arresters is sufficient to absorb the charge on the static-machine plates as rapidly as it is generated, and consequently prevents the rise of potential across the terminals of the machine. A sphere-gap must be used instead of the needle-gap, on account of the line discharge from the latter. Where mercury rectifiers are obtainable, high-potential direct-current may be obtained in greater values. This test is usually not necessary as the second, third, and fifth tests give sufficient data, as a rule, to demonstrate the characteristics of the arrester. Applications of potentials at alternator frequencies of 16 to 60 cycles (test No. 2) give the actual spark potential both by transformation and by equivalent needle-gap. The third test gives natural frequencies, easily regulated to values of a million per second or more. The equivalent needle-gap will usually differ from the values obtained in test No. 2.

In both tests, No. 2 and No. 3, the potential is applied during several cycles of the oscillations. It has been found that some arresters do not discharge easily during the first half-cycle of the oscillation. Through considerations of the dielectric spark-lag and frequency, this characteristic affects the protective value of the arrester. Test No. 5 (half-wave test) brings out this characteristic. By inductive reasoning, it can be shown that an arrester which has a half-wave equivalent spark-gap much greater than the disruptive-stroke equivalent spark-gap is not a good protector for low-frequency strokes. If the arrester does not spark over its gaps during the first half-wave, the insulation in parallel will be punctured unless the time of the first half-cycle of oscillation is less than the dielectric spark-lag of the insulation. In other words, such an arrester may give good protection at exceedingly high frequencies but decreases in protective value as the frequency of the lightning surge happens to be lower.

Summarizing, we have for the study of frequency effects on the arrester that:

Test No. 1 (direct-current static) is usually unavailable and unnecessary.

Test No. 2. Alternator gives two equivalent needle-gaps.

a. The needle-gap corresponding to the voltage by transformation (no arrester connected to the terminals).

b. The equivalent needle-gap as actually measured in parallel with the arrester.

Test No. 3 (disruptive stroke) gives two equivalent spark-gaps, one for each test.

c. The equivalent needle-gap of suddenly applied potential (alternator as source), arrester energized previous to stroke.

d. The equivalent needle-gap of suddenly applied potential (static machine as source), arrester not energized previous to stroke.

The form of the equivalent needle-gap characteristic curves will usually give information concerning the effect of frequency by inductive reasoning.

Test No. 5 (half-wave test) gives one equivalent spark-gap.

e. Equivalent needle-gap which shows the sensitiveness during the early part of any surge.

B. *Effect of rate and acceleration of discharge on the equivalent needle-gap*. The rate of discharge is the value of the current carrying off the quantity of electricity which causes the strain on the insulation. Mathematically, it is expressed as

$$I = \frac{dQ}{dt} = C\frac{dv}{dt}$$

It is the rate of decrease in the quantity of electricity, or it is the rate of decrease of potential. It is evident that the higher the rate of discharge, the less will be the liability of damage to the insulation. The rate of discharge (that is, the current) varies inversely as the resistance in the circuit. The effect of the rate of discharge, as affected by resistance, is shown by the equivalent needle-gap characteristic-curve of the resistance of the arrester, especially using the disruptive-stroke test.

Before an arrester can have a rate of discharge (current) there must be an increase of current from zero, or normal, to the value considered. The rate of this increase is the acceleration of the discharge. Even if the final rate of discharge is high, it will be of little avail if it requires a relatively long time to reach the condition of rapid relief. The aceleration of discharge is the rate of increase of current. Mathematically it is expressed as $\frac{dI}{dt} = \frac{V}{L}$ when V is the potential of the lightning and L the inductance of the arrester in the path of the lightning. Since the potential of a lightning stroke on a line cannot be controlled or limited in any way except by overhead grounded wires or materials, the factor of inductance of the arrester must be reduced to its minimum possible value. Since the inductance of an arrester is normally very low, it will cause no appreciable voltage effect except at very high frequency, therefore the high-frequency disruptive test (No. 3) should be used to measure the inductance. In order to eliminate the other involved factors, viz., dielectric spark-lag and rate of discharge, a wire of good conductivity may be carried over the contour of the arrester circuit and the equivalent spark-gap of this inductance taken. This equivalent spark-gap is inversely proportional to the acceleration. In general, arresters have negligible inductance as compared with the inductance of the earth connection.

C. *Effect of the quantity of lightning discharge on the equivalent spark-gap.* It should be noted that in this the quantity of dynamic electricity is not included. The quantity of dynamic electricity which follows the lightning stroke produces an effect on the endurance and arc-extinguishing power, and should be considered under a different head. If the dynamic discharge causes the lightning surge, the quantity of electricity involved in the excess potential comes under this head.

The effect of quantity of electricity was incidently involved and discussed under rate and acceleration of discharge.

There are three means of increasing the quantity of lightning electricity:

1. By keeping the capacity constant and increasing the potential.

2. By keeping the potential constant and increasing the capacity.

3. By maintaining a current at high potential and allowing it to flow for a time. $Q = I\,t$.

If the increased quantity of electricity is obtained by an increase of potential, the duration of abnormal potential will be extended, since the logarithmic decrement remains the same. If the increased quantity of electricity is due to increased capacity, the natural frequency of the oscillations will be lowered inversely, proportionally to the square root of the capacity.

Increased quantity by increase of time requires the application of continuous power.

The quantity of lightning electricity which may be generated in a laboratory is usually small as compared with the induced stroke on a transmission circuit, but not always. The usual criticisms of laboratory tests are based on this fact. This condition is unfortunate, but does not prevent reasonable deductions from laboratory tests. For example, if increasing quantities of electricity up to the laboratory limit are used, and the equivalent needle-gap of arrester (*X*) continues to rise with the increasing values, it seems safe to conclude that any greater quantity on the line will give a still higher equivalent needle-gap. If the equivalent needle-gap of an arrester (*Y*) remains constant for all available values of quantity in the laboratory, the conditions on the line discharge will be more favorable to *Y* than to *X*, to say the least.

The equivalent spark-gap characteristic-curve taken with either the disruptive stroke test (No. 3) or the half-wave test (No. 5) will show effects of the increase in quantity of electricity. In test No. 3, the quantity may be increased by an increase in potential obtained by drawing out the *G* gap, or it may be increased by using larger condensers. In the second case, the potential may be left constant, but the natural frequency of the discharge is somewhat lowered, according to the formula

$$n = \frac{1}{2\pi\sqrt{LC}}.$$

The quantity of electricity in the half-wave test depends on the electromagnetic circuit, dimensions, and on the value of current in the primary. Greater quantity, then, may be obtained by choosing a larger transformer or by increasing the value of the direct current.

The only known way of reducing the quantity of cloud-lightning charge on a line is by means of an overhead grounded wire or other overhanging material.

D. *What is the nature of the dynamic current-suppressing device?* To make this definite, some of the known devices are herewith enumerated.

1. Arc suppressed by rectifying quality of zinc; example, multigap arrester.

2. Arc suppressed by elongation of the arc to extinction; example, horn gap, magnetic blow-out, and movable plunger or electrode.

3. Arc suppressed by increase of resistance; example, conglomerate materials, analogous to coherers.

4. Arc suppressed by counter electromotive force; example, liquid electrode.

5. Arc suppressed by fuses in series.

6. No arc to suppress; dynamic limited by condenser effect. Example, aluminum cell without series-gaps.

There are at least three features about the dynamic current-suppressing device which should be determined experimentally.

a. Does the device for the dynamic current also restrict the flow of the lightning current in any way?

b How long does the device require to extinguish the dynamic current?

c. Does the extinguishment of the dynamic current set up secondary lightning surges on the system?

To answer question (*a*), the equivalent spark-gap should be taken under the widest range of conditions possible in the laboratory.

To answer question (*b*), a study of the oscillograms of the discharge is necessary.

To answer question (*c*). some knowledge may be gained by arcing in connection with inductances and capacities of variable proportions. Even line tests are feasible, using protected needle-gaps at different points to measure the rise of potential. Oscillograms will sometimes give an indication of surges, or possible surges under more favorable conditions, in the form of a sudden decrease of current.

E. *Endurance of the arrester.* Two conditions of endurance corresponding with the service conditions should be recognized.

1. Endurance to transitory lightning strokes at stated intervals.

2. Endurance to recurrent surges.

From observations of a number of thunder storms, the general conclusion has been reached that two strokes of cloud-lightning follow each other either in rapid succession, one setting off the other, or only after an interval which may be reckoned in several seconds or minutes. The time between strokes will vary with the storms, but an interval of three to ten minutes was usual in one locality.

Starting discharges over an arrester in a laboratory test at intervals as great as three minutes, would make an endurance run of inconveniently great length. An arrester recovers from a stroke of lightning quickly, and it is necessary to give sufficient time only between strokes to dissipate the energy loss in the arrester. In most cases, an interval of 10 sec. is sufficient to dissipate the heat, but in a number of cases the writer has used ¼ sec. with a total endurance of 10,000 strokes.

If the arrester is intended only for intermittent lightning strokes, the only rule that can be adopted is to make the interval sufficient to avoid damaging the arrester by carrying the effect of one stroke over to the succeeding one; such an arrester should be capable of successful operation also when the strokes come in pairs, the interval between the two strokes of each pair being in the range of one to ten cycles of the generator frequency. In the test record, the interval should be noted.

If the arrester is designed for recurrent surges, its endurance is expressed in the number of minutes it will carry the continual train of discharges until the arrester no longer protects or is inoperative. Going out of operation may be the result of total destruction, destruction of some essential part, or increase of equivalent needle-gap to a dangerously high value.

F. *The dielectric spark-lag.* Although there are no commercial methods of measuring the dielectric spark-lag sufficiently developed to present at this writing, the subject is too important in lightning protection to leave without mention. Progress in the development of protective apparatus requires a recognition of its existence, and a further study of the cases where the dielectric spark-lag of an arrester involves a danger to the insulation. Any arrester involving the use of a gap in series has a dielectric spark-lag. Thus, eliminating other defects, dielectric spark-lag is dangerous wherever it is possible to injure normal insulation placed in parallel with the arrester by subjecting both simultaneously to any kind of a lightning discharge. The converse of this statement, that the failure is due to the dielectric spark-lag only, is evidently not true. Each case must be discussed on its own merits based on the previously mentioned tests. The use of one or more series gaps necessarily involves a value of dielectric spark-lag. In reporting on the lightning-arrester, it is necessary, for the present at least, simply to state whether the arrester has or has not series gaps; the use of series gaps does not condemn the arrester, although it is a distinguishing feature.

As a brief summary, recommendation of tests of lightning arresters should include at least the following:

1. The equivalent spark-gap characteristic-curve by the disruptive-discharge test.
2. The equivalent spark-gap at generator frequency.
3. The maximum discharge current at normal voltage and at double normal voltage.
4. The half-wave equivalent spark-gap.
5. The endurance of the device.

The principal protective apparatus to be considered are as follows:

1. Lightning-arresters.

The choice of arresters will usually lie among the four following types:

a. Multigap arrester.
b. Aluminum arrester (no-gap type and gap-type).
c. Liquid-electrode arrester.
d. Magnetic-blow-out arrester.

2. Lightning-arrester choke-coils or reactances.
3. Overhead grounded wires, one or more, with or without lightning-rods.
4. Overload switches, either single-phase or multiphase.
5. Insulator protectors, horns or gaps, with or without fuses.
6. Static dischargers.
7. Earth connections.
8. Horn arresters with resistance.

The classifications of the circuits to be protected are as follows:

1. Constant-potential alternating-current overhead systems $\begin{cases}\text{grounded neutral}\\ \text{non-grounded neutral.}\end{cases}$
2. Constant-potential alternating-current cable system $\begin{cases}\text{grounded neutral}\\ \text{non-grounded neutral.}\end{cases}$

3. Constant potential direct-current systems.
4. Constant-current systems.

Comments on the protective apparatus. *a.* The multigap arrester has been used for years, and has been described and discussed elsewhere down to the latest designs. Its excellent qualities for discharging transitory lightning are well known.

b. The aluminum arresters are particularly well adapted to discharging continual lightning. They do not replace the multigap arrester, but complete the protection of a system by taking care of lightning which endangers the multigap arresters. Nearly all cases of destruction of the multigap arresters of the old design have been due to continual lightning. Every constant-potential system should have at least one installation of aluminum-cell arresters. This arrester is preferably installed on the bus-bars so as to take care of all feeders, and the multigap arrester on the feeders outside the switches for protection of the particular feeders. The aluminum arrester is a winter and summer arrester, as continual lightning is not directly due to cloud-lightning. The two types of aluminum arresters are the no-gap and gap types. The gap type is the cheaper and has a less maintenance expense, but the no-gap type is more effective.

c. The liquid-electrode arrester is recommended for potentials above 35 kilovolts, where the design of a multigap arrester is difficult.

d. The magnetic-blow-out arrester has been used for several years. It is adapted to constant-potential direct-current systems.

2. Lightning-arrester choke-coils or reactances have the function of retarding high-frequency lightning traveling toward the station. This retardation gives the lightning-arresters time to relieve the lightning potential before it strikes the apparatus. This high-frequency lightning seems to come invariably from cloud-lightning, therefore the installation of choke-coils on the cable systems is unnecessary and not to be recommended. In many cases, the installation of good lightning-arresters both inside and outside choke-coils is to be recommended.

3. Overhead ground wires. If a wire be placed underground, it is protected from the static charge of cloud lightning. If the insulated wire is simply placed in a metallic sheath and hung overhead, it is still protected from electrostatic charges from the clouds. Both these methods are often impossible of employ-

ment on account of the unjustifiable expense involved. The next best thing to do is to put the ground over the line wire. The farther above the line wire the grounded wire is placed, the better is the partial protection. Dr. Steinmetz recommends that an overhead grounded wire be so placed that two imaginary lines drawn from this wire 45° down from the horizontal will include all line wires between them. Each additional overhead ground wire, properly placed, gives some additional protection against induced static electricity from the clouds. The investment is the controlling factor in the choice.

The overhead grounded wire also has the function of protecting wooden poles from shattering by direct stroke of cloud-lightning. It also has the possibility of carrying a direct stroke of cloud-lightning to ground past the line wires without shattering the insulators or causing a short-circuit. More data regarding this point are needed.

Lightning-rods at each pole add a slight probability that a direct stroke will strike at the pole and not between poles.

If the overhead grounded wire is earthed at every pole, direct strokes of lightning are likely to find a more direct path to earth. The wave-front of a direct stroke is usually so steep that the charge finds the natural inductance of the horizontal wire a great impedance, and consequently it is likely to side-flash to other lines and also over insulators to its natural terminus, the earth. If the earth connection is made at every third pole, there are of course more chances that a direct stroke will hit a midway point and have a greater distance to travel parallel to the line wire before it reaches the earth. The parallel movement of the charge gives electromagnetic induction on the power wires. Practically all reports of damages to lines by direct strokes confine the line damage to about seven successive poles. This fact is suggestive.

4. Overload switches are a part of the protective apparatus, especially on grounded neutral systems. Multiphase switches are usually installed and are to be recommended on all systems, like a cable circuit, where a short-circuit between phases follows quickly after a short-circuit from phase to neutral. On overhead grounded neutral systems, phase-to-phase short-circuits are less likely to occur, and consequently, if three single-pole switches are used, the phase short-circuited may be opened automatically; and the load, if not excessive, may be carried on the remaining two wires with a ground return for a time.

5. Insulator protectors. An insulator protector is a single gap or horn gap placed beside the insulators and set with a gap-length such that a spark will just prefer to jump the gap to arcing around the insulator. The insulator should be in its wet condition. The use of this protector is based on the principle that if the arc must take place at the insulator, due to any high potential, it will guide the flames so that the insulator will not be cracked by the heat. The arc is then interrupted either by a fuse or by automatic trip-switches in the station. If no damage is done to the generator or transformers, the line can be immediately put back into service. Otherwise, the line is out of service until the linemen locate and repair the damaged insulator. On most alternating-current railway circuits, a momentary interruption of service is not very objectionable.

There are some evident objections to the use of the insulator protector.

In general, every electrical system should have some lightning protection. There is a certain minimum of protection below which it is not advisable to go. The amount of protective apparatus above this minimum will depend primarily on the value of the transmission apparatus and the value of continuity of service. Since there is a uniformity in these values in the various installations throughout the country, there is consequently a general uniformity of practice. There are, however, many special cases which require the careful consideration of every device described above. Such examples are found in large factories and industries depending entirely on continuity of electrical power, also in large lighting plants in cities. Thoroughly efficient protection is not much more expensive than partial protection, and is cheaper than carrying duplicate plants and apparatus, in addition to the repair bill and almost inevitable interruption of service when apparatus is destroyed. Arresters are of the nature of insurance. A reasonable percentage of the cost of the apparatus, cables, lines, etc., with the factor of the cost of repair of each kept in view, should be added to the monetary value of continuity of service. The sum thus found should be the limit up to which it is justifiable to make expenditures for protection and inspection.

Recommendations for protection of electrical plants in general. These recommendations will vary with the class of circuit to be protected.

1. Constant-potential, alternating current, overhead systems.

The first consideration is the question of connecting up grounded neutral or non-grounded neutral (this includes straight delta connection). The answer is somewhat influenced by the kilowatt capacity of the generating apparatus and the multiplicity of the circuits. In general, it may be stated that the distinguishing troubles on a non-grounded neutral system are primarily potential or internal-lightning troubles; these may finally result in a short-circuit which becomes a current trouble. On the other hand, in the grounded neutral system the initial trouble is usually a short-circuit which may become an internal-lightning surge when the abnormal current is suppressed. Until the advent of the aluminum arrester, there was no way of taking care of the continual lightning on a non-grounded neutral system, due to a phase becoming accidentally grounded, and consequently practice has been favoring the grounded neutral connection. It seems safe to predict that the non-grounded neutral connection will now become more favored on account of the possibility of operating for an indefinitely long time with a grounded phase.

Insulators often fail one at a time, and such failure causes a short-circuit in the grounded neutral connection. The subject of overload-switches has already been discussed above.

On a non-grounded neutral system, the aluminum arrester is absolutely essential. On a non-grounded neutral system, it is advisable to use an aluminum arrester to take care of the preliminary continual oscillations which sometimes precede a short-circuit, and afterwards to take care of the low-frequency energy surge that sometimes results from the interruption of the short-circuit current. In the case of multiple circuits, an aluminum arrester in a station may be used, connected directly to the bus-bars. Multigap or other arresters for transitory lightning should be installed on each line or feeder, and lightning choke-coils should be used in each phase between the arrester and bus-bars. Line arresters should be used on the line at high altitudes, exposed lengths, fractional multiples of the line length to catch standing waves, and in the usual path of thunder storms. Transitory-lightning-arresters should be installed on all incoming and outgoing lines in conjunction with choke-coils in every sub-station. An aluminum arrester is probably unnecessary, in general, in each sub-station, but in some cases it will be advisable to install another arrester at the extreme end of the line.

When low-potential systems are fed from high-potential systems, special precaution should be taken to prevent the destruction of the arrester, and then of the low-voltage apparatus over the entire system by the accidental impression of the high voltage on the low-voltage system. This may happen either through electrostatic induction or direct connection of the two systems. Continual and continuous lightning are produced on the low-voltage system. The multigap arrester without series resistance will short-circuit by welding the cylinders and thus save the apparatus. An aluminum cell will take care of this condition without interrupting the service, but the arrester must be of special design, as it may have to operate continuously at its critical voltage until the fault is removed. If it is only electrostatic induction through the step-down transformers, the design is easy, but, if it is a direct connection between one phase of the high-potential system and the low-potential system, the aluminum cell must be capable of carrying the condenser current of the high-potential line until the fault is removed.

One substantial overhead wire well-grounded is a justifiable investment on nearly all overhead systems. Two driven iron pipes as earth connections are recommended, or one pipe and the usual wire to the bottom of the wooden post. Using large copper plates buried in the earth is as a rule unnecessary.

Earths. Make an earth connection as near the arrester as possible, even if it must be a relatively poor earth, then extend the earth connection to two good earths. It is advisable to measure the ground resistance each year before the thunder storms appear and to be assured that it is low.

Constant-potential cable systems. The choice of grounded or non-grounded neutral is again up for choice, as the conditions in a cable system are quite different from those of an overhead system. From a protecting standpoint, the difference lies in the fact that the phases are as a rule throughly isolated from one another in the overhead system, and an arc fed by the capacity current of the line can play from one phase to ground without affecting the insulation between phases, but in the cable the capacity currents are much greater, and an arc from phase to ground quickly melts and burns away the insulation between phases. In the usual multiple-feeder system, there is not time in this short interval to locate and disconnect the faulty feeder. Since a short-circuit is to result anyway, and open the circuit-breaker, practice has favored the use of the grounded neutral connection. This avoids most of the continual surges due to a grounded phase on a non-grounded neutral. The aluminum arrester will protect against the continual surges, and, if there are only a few feeders, some evident advantage may be gained by using the non-grounded neutral connection.

The circuit should be broken as quickly as possible after an arc starts, or the heat from the flame will cause widespread damage to adjacent cables and wires. This is especially true on large, high-current systems where even normal current could quickly burn up considerable cable. The engineer should take note of the effect of the heat of an accidental arc, and use non-inflammable separations for the cable. Asbestos covering or brick barriers are to be recommended in manholes or at terminal bells.

Unless there is some special reason for not doing so, the cable sheath should be thoroughly and frequently earthed. It is undesirable to make the sheath carry currents of fusing values, or to allow even a small arc to play upon the sheath to the earth in any spot, especially where inaccessible.

Except the transitory lightning due to switching, all surges on a cable system are continual. Therefore, the multigap, or any other arrester involving an arc in the discharge, is not so well suited for this system as the no-gap aluminum arrester. No choke-coils need be used on a cable system.

Mixed cable and overhead system The only addition to what has been said of each system is the statement of the advisability of installing arresters at the junction point of the two systems.

4. Constant-potential direct-current systems have been satisfactorily protected by the single-gap arrester, notably the magnetic blow-out type. In the future, it is probable that the no-gap aluminum arrester will find an application where cloud lightning is especially severe and where the conditions warrant the extra expense.

5. On constant-current systems, the peculiar conditions permit the use of a simple horn gap with a suitable series resistance.

Although this paper has been carried to an unusual length, not all the salient features of each subject treated have been discussed. It is hoped, however, that enough has been said to assist in bringing the practice in protective apparatus out from the somewhat indefinite speculative stage and to establish the foundation of methods and tests which will place the engineering on the same reasonable basis as that of other electrical branches.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907

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PRACTICAL TESTING OF COMMERCIAL LIGHTNING-ARRESTERS

BY PERCY H. THOMAS

Introductory. The question as to what tests for commercial lightning-arresters might be properly incorporated in the standardization rules of the American Institute of Electrical Engineers has lately been considered by the Standardization Committee. The committee finally decided not to adopt any lightning-arrester tests in the new edition of the rules adopted June 21, 1907. However, the sub-committee on lightning-arresters hopes to get a full consideration of the subject for the benefit of a later Standardization Committee. The present paper, together with another paper on the same subject by Mr. E. E. F. Creighton, is prepared at the request of the sub-committee to serve as a basis for discussion. As no lightning-arrester tests have ever been included in the standardization rules, the initial treatment should now receive especially careful attention.

Some idea of what constitutes suitable subject-matter for the standardization rules of the Institute must be assumed at the outset. It is the opinion of the writer that the purpose of the standardization rules should be to give such directions and information for the comparison and test of commercial lightning-arresters as may be likely to be of general practical use, and which are of such a character as to be generally agreed to and accepted by engineers having experience with the use or design of lightning-arresters. This subject-matter need not be limited to specific tests or specifications, but may properly include general considerations, suggestions of forms of making tests, of apparatus, etc. Individual personal opinions, as to the superiority of particular designs of arresters, specific tests about the value of which there is not a general agreement, untried tests, and, in general, purely theoretical considerations should be omitted.

Research work, covering the effects of various conditions on the performance of lightning-arresters, the investigation of really new types, for example, electrolytic arresters, and the best conditions for determining the detail of designs, etc., is of great importance and should be actively encouraged. But such matter properly finds no place in the standardization rules.

All information and tests embodied in the standardization rules must be sufficiently general to be applicable under all conditions within their terms; for example, a test applicable only to high-voltage alternating-current arresters should not be recommended in such broad terms as to be applied to direct-current railway arresters.

This matter must be capable of being readily understood by any electrical engineer having experience with plants, likely to require the lightning-arresters under consideration. No such person should be expected to have to make a special investigation of new types of apparatus or new methods of test to carry out the rules. All rules should be such as not to favor any particular manufacturer's apparatus.

Tests may be made to determine:

1. The condition of individual arresters.
2. The effectiveness of a particular design.
3. The characteristics of different types.

In general, there will be little occasion for testing the condition of individual arresters, since inspection will usually reveal any defects in the materials or construction. The relative advantages of the different broad types of arresters will in most cases be determined by general considerations and consensus of opinion, rather than by definite tests. It is therefore with individual designs that practical tests on commercial arresters will be found most useful, and here such tests will be of very great benefit. For example, from time to time new commercial arresters appear, advocated by comparatively irresponsible persons. These arresters very often have little protective value. Such arresters, especially on lower voltages, although they are by no means confined to such voltages, find a ready sale entirely independent of their merits, and the more frequently, since engineers of low-voltage plants are often not at all familiar with the lightning-arrester problem. If a standard test generally accepted and capable of easy application can be determined, the detection of such practically worthless arresters will be a comparatively easy matter. Similarly, the necessity of commercial trials on a large scale of special forms of high-tension arresters which have a very limited protective power, may be eliminated by suitable comparative tests. Again, if generally accepted tests were at hand for the criticism of commercial arresters, the designs of many of these arresters would undoubtedly be overhauled and perfected so as to appear to advantage under such tests. If the tests were wisely chosen, a distinct advance in the art would follow.

In testing the effectiveness of individual designs, one of the most important features to be determined is the insulation strength of the apparatus to resist the static strains existing during actual discharge.

Tests should undoubtedly be made to cover auxiliary apparatus as well as arresters proper, for example, line choke-coils.

Conditions of actual operation. A recital of the various ways in which lightning and other static disturbances can affect an exposed commercial circuit has been often made. Practically all result in the equivalent of the production of a sudden rush of electricity, or wave, or surge along a line wire. Such a surge usually passes both ways in the wire until it is discharged, dissipated, or reflected. There is obviously no upper limit to the electromotive force which may be applied to a line wire by lightning, and the wave or surge may be theoretically of any frequency. As a matter of fact, however, since extremely high frequency—for example, 100,000,000 million cycles—must necessarily be associated with extremely small electrostatic capacities, in the writer's opinion such very high frequency disturbances need not be here considered. (See appendix I.)

The distinctive characteristics of the static surge or wave are its abnormal frequency and the fact that it is not directly supported by the power of the generator. It should, of course, be remembered that these surges not only produce strains to ground and between line wires, but they frequently cause concentration of potential between turns of windings in coils, especially near the terminals.

Resonance, being usually supported directly by the power of the generator, will not be cared for by lightning-arresters and is here omitted from consideration.

There is another possible source of potential rise of a static character; namely, the sudden interruption of a current flowing through inductance, such as the inductance of a transmission line. It is evident that a short-circuit including the whole or a portion of the transmission system, will store a relatively large amount of energy in the inductance thereof if by any means such a short-circuit current be abruptly interrupted, a very high potential will result, being limited only by the electrostatic capacity of the lines and their insulation strength. It is the opinion of the writer, however, that this condition never occurs where large currents are involved, since the condition predicated for producing the short-circuit provides also a discharge path for any voltage rise, and since the very energy stored in the choke-coil will tend to maintain the current uninterrupted until the major portion of this energy is dissipated. When, however, in the case of the opening of such a short-circuit as in an open-air arc, the extension of the length of the arc proper has reduced the current to a value where it becomes relatively unstable, there will be a tendency for the arc to go out suddenly, causing the *remnant* of the energy, originally remaining stored in the inductance, to produce a rising potential. This residue will, however, never be more than a small portion of the maximum energy stored. A great many direct tests of the opening of circuits through enclosed fuses and circuit-breakers, where conditions have been definitely known to be as assumed, have shown practicably negligible rises of potential. The fact that high voltages have appeared in electric accidents coincidentally with short-circuits and arcs is no proof that these high voltages have resulted from the sudden interruption of heavy short-circuit currents.

The severity and general range of the static disturbances actually materializing within an electric system is definitely limited in certain ways.

A. The maximum voltage of a surge passing along a line must be limited to the voltage which will cause a discharge to earth over the line poles. That this is an effective limitation is shown by the great number of transmission poles which have been shattered by lightning. It is natural to suppose that on this account, transmission lines having steel poles will not make as heavy demands on the terminal protective apparatus as lines having wooden poles, since the discharge to earth can presumably occur much more readily on the former. It remains to be seen, however, whether the added annoyance of grounds and cracked insulators where the steel poles are used, does not more than offset the advantage of the discharge from the wire over insulator to ground.

B. Disturbances of very small energy, and hence very high frequency discharges, can be neglected, since the electrostatic capacity of the terminal line wiring and apparatus will be such as to absorb their energy without serious rise of potential.

In general, then, it is the opinion of the writer that we are safe in concluding that we have to deal only with static waves, or surges of potential not over a few times line potential, on extra high-tension circuits: namely, high enough to discharge to ground over the insulators, such surges having frequencies usually very high with regard to normal frequency, but not what is generally understood by extremely high frequency; for example, practically never reaching fifty million cycles a second.

Lightning-arresters should discharge without serious rise of potential and without otherwise disturbing the system, this specific type of "static,"—not static disturbances in general, nor all kinds or forms of that can be devised or produced under laboratory conditions,—but merely static discharges actually occurring under the limitations imposed by commercial plants.

Choke-coils, static interrupters, or reinforced insulation must serve to protect windings from local concentration of potential under the same limitations as to the character of the static disturbances as above.

It should be stated in this connection that to enable an arrester to exert its protective function properly, it is necessary that all the insulation of the system, including the apparatus and the lines shall be high, and especially that it be high against *static disturbances*. Bushings and surfaces are often broken down much more easily by static than by normal frequency strains. It is by the strengthening of the insulation of the system that immunity from lightning has been in the past most readily obtained and will in the future be most effectively increased.

TESTS

Discussion and specification. The discussion in this paper will be confined to lightning-arresters for electric lighting and power circuits, alternating and direct current. Such arresters may be of many types having radically different characteristics and structures. For the sake of clearness, it will be well to enumerate the principal of these types:

Multigap arresters, with series or shunt resistances or both. These arresters are used practically only on alternating-current, constant potential. The multigap feature is, of course, introduced on account of its non-arcing power.

Arresters relying for the suppression of the generator arc upon the blowing of a fuse or upon the opening of a circuit-breaker.

So-called horn arresters.

Magnetic-blow-out arresters.

Electrolytic arresters.

Many special types, including such arresters as the water-jet, the Gola, the Wurts railway arrester, and many others relying on special materials or special forms for their non-arcing power or discharge characteristics.

The features of arrester apparatus most susceptible of satisfactory tests are perhaps:

A. The initial break-down voltage.
B. The static equivalent during discharge.
C. The circuit-opening power.
D. The insulation strength.
E. The ability to stand repeated discharges.
F. The choking power and insulation strength of choke-coils and equivalent apparatus.

HOLDING NORMAL VOLTAGE

General considerations. The determination of the voltage necessary to cause an arrester to discharge is of importance; first, as ascertaining the minimum voltage at which protection begins; secondly, the margin of safety which the arrester has in order to secure itself against continuous break-down. The second consideration is of special importance in the high-tension arresters, especially voltages of 30,000 and above.

On very high-tension circuits, the power of multigap lightning-arresters to hold the normal line voltage is very greatly affected by attendant conditions; for example, the electrostatic capacity of the intermediate unconnected cylinders forming the gaps causes a break-down to occur at a much lower voltage on high frequency than on low frequency. This subject has been fully discussed before the Institute, for example, in connection with the following papers:

"Methods of Testing Protective Apparatus" by E. E. F. Creighton; see discussion by Chas. P. Steinmetz, TRANSACTIONS, Vol.

XXV, 1906; "Protection against Lightning, and the Multigap Arrester," by D. B. Rushmore and D. Dubois. TRANSACTIONS, Vol. XXVI, 1907, and "Multigap Lightning Arresters with Ground Shields," R. B. Ingram, *Electric Journal*, April, 1907.

Since the capacity of these gap cylinders is increased by the nearness of grounded objects, the placing of arresters near a wire or transformer case or similar object, or more particularly in the neighborhood of other arresters or line wires on another leg of the circuit, tends very greatly to increase this effect. The effect is so marked that an arrester entirely capable of holding the line voltage with a good margin of safety, if installed apart from other objects, will be utterly unable to hold normal voltage, if installed in close proximity to another arrester connected to a different leg of the line. From this, it follows that tests to determine the power of an arrester to hold normal voltage must be made under conditions equivalent to those under which that individual arrester is to serve. The writer suggests that, on voltages of 40,000 volts or higher, an excess of air-gaps may be provided, and the exact number required to give a proper margin over line voltage be determined by trial after final installation.

Too sensitive an adjustment of the series-gaps of an arrester on very high tension circuits will be the cause of the greatest annoyance, and probably will result in the destruction of the arrester. The resulting frequent discharges of the arrester will oftentimes be laid to abnormal static, due to some unknown cause, when as a matter of fact the only difficulty is the ease with which the arrester discharges on slight impulses of high frequency or even fluctuations of abnormal voltage. This condition has in the past, often been a source of great annoyance in commercial plants where it has frequently not been recognized; it should always be carefully borne in mind.

Description of test. The actual measurement of the breakdown voltage of an arrester can best be made at normal frequency. In making this measurement, the primary object is to determine the margin of safety in the arrester over the normal line voltage as read on a voltmeter. Thus in this particular instance the use of the needle-point spark-gap for measuring the voltage as provided in the standardization rules, though always of value, is not as directly the criterion sought as the voltage determined by the voltmeter. In making such a measurement, all the conditions provided in the standardization rules under "Insulation Tests" should be followed, where applicable. The writer suggests that, where practicable, the determination of the breaking down voltage of arresters on 40,000 volts or over be made from the main generator of the system with the arresters and neighboring apparatus in final position.

It is true that high-tension multigap arresters will break down at a much lower voltage on high-frequency electromotive force than on normal frequency; but, in the opinion of the writer, since this phenomenon is in the direction of safety, and, since it has been established by actual experience on high-tension plants that this fact does not cause discharges on arresters frequently enough to be troublesome, this may be accepted as a favorable characteristic of such arresters. This matter is, however, properly a subject for investigation and research.

MAXIMUM IMPEDANCE OFFERED TO A DISCHARGE—NEEDLE-GAP EQUIVALENT

General considerations. The maximum impedance offered to a discharge determines the protective power of an arrester, and is therefore of the greatest importance. On the other hand, since so little can be definitely determined as to the type of discharges actually to be met, and so much depends upon the characteristics of the circuit and apparatus being protected, it is impracticable at the present time to devise *absolute* tests of a general character which are not likely to be uncertain or misleading. It is of course easy to choose condensers and circuits, and apply static to arresters under a great variety of conditions with presumably considerable variation in results, but in the opinion of the writer such tests, except where they can be shown to be reasonably within the conditions existing in a transmission line, should not be specified for the testing of commercial arresters, but should be considered as proper subjects for investigation and research. However, comparative tests between arresters may be often made to great advantage.

If an arrester be subjected to a high-frequency discharge from a condenser, and its static equivalent measured by the equivalent needle-gap method, the numerical result will depend upon the character and method of operation of the testing apparatus; for example, it will depend on the electrostatic capacity of the condenser, the inductance through which it discharges, the voltage to which it is charged, the auxiliary circuits providing for the charging of the condenser, and the disposition of the arrester itself. Since it is manifestly impossible to determine upon any reasonable number of definitive conditions as representing the transmission line under all conditions, no general absolute test should be attempted as such; that is, no attempt should be made to treat each arrester as having so many units of protecting power irrespective of conditions of service and of test.

The study of arresters through the agency of condenser discharges has been an absolute necessity in the progress of recent years. This progress has been notable. Tests with any reasonable form of condenser discharges, as distinguished from applications of normal frequency, will show practically the same characteristic results, although numerically different frequencies and different circuit arrangements, etc. will show variations. Consequently, to get what advantage is practicable out of such tests, the natural course would seem to be to use some condition, or conditions, of condenser capacity, etc., known to be reasonably well within the conditions of actual operation and reasonably easy of realization, and then to make comparative tests for what they may be worth. By this means, a large part of the value of a complete range of static tests will be obtained. Any further data that might be found by multiplying the tests under different conditions, would probably produce only small changes in the actual conclusions; such additional tests are more properly subjects for investigation and research than for practical tests of commercial arresters.

Taking up these tests more in detail, the various types of arresters will be separately considered, since their needle-gap equivalents are controlled by radically different features.

1. *Arresters offering no impedance to the discharge.* Such arresters rely on special features for suppressing the generator arc. Examples are the fuse type, the horn type, and the magnetic blow-out type. If a horn arrester has also a series resistance, it is no longer properly a horn arrester but a series resistance arrester. It is obvious that the maximum impedance offered to a discharge by this type is practically equal to the initial discharge voltage, and no further test is required than has been already indicated under the head of holding normal voltage. This type of arrester is especially effective in discharging the line.

In connection with these arresters, the question must be raised, however, that it is theoretically possible for the device relied on for interrupting the generator current to introduce a rise of potential. This question can be determined finally only by experience. The definite data available at the present time, derived from direct tests, have, as far as the writer is aware, failed to indicate any serious rise of potential from the operation of fuses, horn, or magnetic blow-out arresters. The question is, however, somewhat a matter of controversy.

2. *Arresters with series resistance.* Series resistance must necessarily offer some impedance to a static discharge. The amount of this impedance will depend upon the value of the resistance, on its inductance and its capacity, on the abruptness of the application of the charge, and upon the inductance through which such charge must pass. Any inductance in the series resistance will tend to impede the discharge; any capacity, however, either internal or with other objects, will tend to facilitate the discharge. The higher the frequency, that is, the greater the abruptness of the discharge, the greater will be the relative importance of the inductance and capacity in the series resistance in comparison with the ohmic resistance.

It is evident that the danger to apparatus introduced by the series resistance will be negligible if the discharge be small enough, or may theoretically be dangerous with the lowest resistance if the discharge be abrupt and heavy enough. Since both the magnitude and abruptness of the discharges which can be produced in a commercial system are limited by certain maximum conditions, it becomes an open question just how much danger will result in practical operation from a definite series resistance.

Series resistances for lightning-arresters have been designed on two principles; first, sufficient to cut down the generator current following a discharge, to render the device easily non-arcing, and to prevent all burning of cylinders; secondly, usually with multi-gap arresters, to allow as free a discharge as possible while still maintaining the non-arcing quality. In the latter case the shunt resistance has ordinarily been used as well, and helps decidedly in cutting down the minimum allowable series resistance. Experience shows that the first mentioned high series resistance does seriously impede the static discharge on commercial lines and it has been practically abandoned as a means of principal protection, though somewhat used to carry off the so-called slowly accumulated charge. The low series resistance is much used on all types of alternating-current circuits except those of lower voltages; it can hardly be considered at present as finally determined, whether or not the present "minimum value" series resistances offer serious opposition to actual discharges on commercial systems. In most cases they do not.

The determination by test of the impedance offered by a series resistance arrester to a static discharge is hardly practicable, since such resistance will ordinarily constitute practically the major portion of the resistance in the test circuit, so that, whatever the discharge voltage may be, it will of necessity be impressed upon the series resistance. The needle-gap equivalent would then be merely a measurement of the voltage and quantity of current in this particular test, and not any inherent characteristic of the arrester. Some idea of the relative value of two arresters may be obtained by connecting them in series, passing a discharge through, and measuring the needle-gap equivalent of each arrester. As far as the writer knows, this particular form of test has rarely been made. Obviously, a comparison of the ohmic value of the series resistances of two arresters, generally similar, will give a good idea of their relative effectiveness. Where the types of series resistance are, however, entirely different, a comparative test by putting the two in series and subjecting them to the same discharge, or some equivalent test would be necessary for forming a trustworthy judgment.

3. *Special forms of arresters.* Under this head are included, as above, arresters relying on special forms and special materials for their non-arcing power, and arresters having an unknown construction. Here will be classified many new types of arresters, especially low-voltage forms which appear from time to time, but are not founded on well-recognized principles and are presumably of doubtful utility.

These types are generally found to be intermediate in their characteristics between groups 1 and 2, above. They are not like group 1, in which the maximum impedance to a discharge is practically independent of the character or strength of the discharge, nor are they quite like group 2, in which the needle-gap equivalent is more or less directly proportional to the severity and abruptness of the discharge; their equivalent is usually found to increase slowly with increasing severity of discharge. It is in these special groups that direct tests by discharge of condenser through the arrester are of the most service. Such tests may be made to give a measure of the impedance offered to the discharge, as compared with that offered by some standard well-known arrester, thus giving data for the judgment of their effectiveness where inspection and the results of commercial service are insufficient to determine the merits of the arresters.

In view of the compactness of construction of most lightning-arresters, there is always an opportunity for a discharge to break down insulation or jump an air-space, short-circuiting a portion of its normal path. Such action is of course likely to destroy the arrester and shut down the system, since the non-arcing features are ordinarily be thereby crippled. The test with a severe condenser discharge may be made to serve the function of testing the insulation of the arrester. This is one of the tests most needed and most easily made, and should be strongly recommended. In actual practice, a great many arresters have failed on both high-tension and low-tension circuits from discharges jumping between parts or to ground, and allowing the generator current to follow. When these tests are made without the power lines being connected to the arrester, care must be taken to detect the occurrence of internal sparks, as they may not otherwise be noticed.

Description of test. The test to determine the impedance offered to a discharge may be best made by discharging a condenser directly through the apparatus to be tested, and measuring the maximum voltage across this apparatus by a needle-point spark-gap. The measuring spark-gap may either be so set as to take the discharge half the time, while the apparatus takes it the other half, or it may be so set as just to fail to take any discharges. The former condition is presumably the better one, since to make a spark-gap take all the discharges when connected in parallel with an arrester, it is sometimes necessary to increase the gap a very considerable percentage. This percentage will depend upon all sorts of conditions not definable or controllable, so that a very considerable source of variation will be introduced into the measurements, if the method of entirely suppressing the spark in the measuring gap be adopted. The needle-point gap taking half of the discharges will be the comparative measure of the impedance voltage offered to the discharge.

Spark-gap. The condenser should always discharge over a spark-gap to reach the apparatus to be tested. This is the element which introduces the high frequency. This spark-gap should preferably be large enough to cause a voltage to be impressed upon the arrester very much higher than the normal voltage of the circuit upon which it is to be used; where possible perhaps three times normal voltage. The tests will of course be of value even if a considerably lower discharge potential be used.

Condenser. The electrostatic capacity of the condenser should preferably be considerable, because it is intended to reproduce to some extent the more severe conditions of practical experience. A pair of high- or low-tension line wires will ordinarily have a capacity in the neighborhood of one hundredth of a microfarad per mile. It is thus seen that where several lines are connected to the same bus-bars near the arrester, a considerable capacity may discharge over the arrester. It is difficult to tell just what portion of a line wire near the discharge point should be considered to discharge directly through the arrester, since the inductance of the line becomes very considerable and tends to delay the discharge of the more remote parts, allowing the arresters more time to pass off the excess. (See Appendix II). It is suggested as a compromise value that where practicable a few hundredths of a microfarad be tried. This figure is admittedly open to discussion. Capacity can be most easily measured by determining the charging current taken on a *true sine* electromotive force at a known frequency and voltage; one microfarad takes three-eighths of an ampere approximately at 60 cycles and 1,000 volts.

It may further be added, that it seems practically very unlikely that any considerable length of transmission line can be raised at one time to an excessively high potential by any static disturbance. The total length of line simultaneously affected could hardly exceed a few miles at most. Where so much capacity as here recommended is not available, since all such tests must be relative, a considerably smaller condenser will give valuable results. High voltage rather than extremely large electrostatic capacity is recommended.

Abruptness. The condition of extreme abruptness in a test, which is one of the severe conditions, is obtained by having no impedance, other than the arrester directly, in the discharge path of the condenser and by limiting the length of the connecting wires in such path to a few feet. The initial abruptness of the discharge (though not the frequency of oscillation) depends solely upon the inductance and resistance in the discharge path; it is not lessened but rather increased by enlarging the capacity of the condenser. It is of much more importance in making the discharge sudden, that the inductance in the discharge path of the condenser be eliminated, than that the electrostatic capacity of the condenser be large. The character of a discharge is indicated by the sound. The " crack " should be extremely sharp and loud.

Circuits. In providing means for charging the condenser conveniently (except where using a static machine), it will usually be necessary to prevent the current supported by the charging apparatus from being maintained through the lightning-arrester after a discharge. This might oftentimes burn out a resistance.

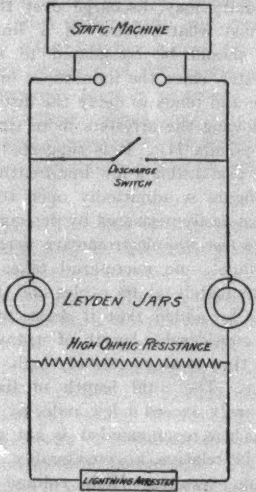

FIG. 1—Diagram of circuits for testing impedance offered by lightning-arrester to a discharge—static machine and leyden jars

A variety of connections may be utilized for these tests, two of which are shown in Figs. 1 and 2. Others may be devised.

Where laboratory apparatus and laboratory skill are available and the voltage is not too high, the arrangement in Fig. 1, utilizing a frictional or static generator, will be found convenient and compact. Under other conditions, however, static machines are often not available; they are very troublesome except in the hands of persons especially expert, and in general will be found less satisfactory than the connections in Fig. 2. The arrangement shown in Fig. 1 is substantially that described by Mr. Creighton in a paper before the annual convention of this Institute in 1906, Vol. XXV of the TRANSACTIONS.

It is, of course, possible to utilize the circuits of Fig. 1, substituting for the static machine a step-up transformer connected to an alternating-current main. A switch will then be used across the high-tension leads of the transformer to start the discharge. There must usually be some current-limiting device in connection with the transformer, to prevent too much current flow on the closing of the switch. This arrangement should give a satisfactory source of static discharge.

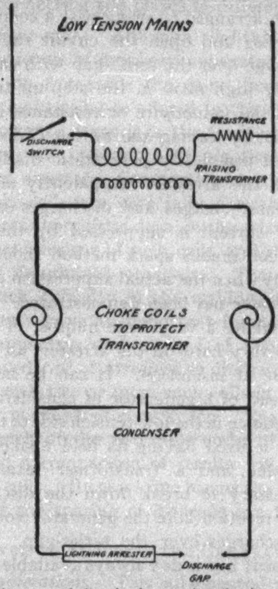
LOW TENSION MAINS
RESISTANCE
DISCHARGE SWITCH
RAISING TRANSFORMER
CHOKE COILS TO PROTECT TRANSFORMER
CONDENSER
LIGHTNING ARRESTER
DISCHARGE GAP

FIG. 2—Diagram of circuits for testing the impedance offered by a lightning-arrester to a discharge—alternating-current mains and step-up transformer

In Fig. 2, alternating-current is used to charge the condenser through a step-up transformer and the discharge is produced by the closing of a switch, as shown. This switch must ordinarily be opened rapidly, to prevent the generator current from following a discharge over the series-gap through the arrester. The resistance or inductance in series with the primary of the transformer also serves to limit the generator current. Such a switch may easily be made by mounting a contact on the end of a pole some feet in length, arranged to swing past a coöperating contact point; this will close and open the circuit rapidly enough to get a single discharge over the series-gap with each closing.

By using a very high ratio in the step-up transformer and suitable values of the inductance or resistance in the primary, it is often possible, by leaving the switch closed, to produce a rapid succession of practically pure static discharges over the series-gap through the arrester. Apparently under these conditions the condenser charges and discharges each alternation, and all generator current is suppressed by the inductance or resistance. This continuous spark method should be used with great care, and only when the actual suppression of the generator current in the arrester has been demonstrated. This condition is favorable for making a very large number of discharges in a short time, but is very hard on the arrester; as, for example, in case of a puncture of insulation. It can be more readily obtained when, instead of a generator of considerable power and choke-coils or resistance in the low-tension side of the transformer, a small generator is used having its field weakened very much below normal value, and a transformer ratio chosen much greater than necessary to break down the discharge gap. In this case, the field reaction kills the generator voltage as soon as the condenser discharges over the series-gap. This is a very effective arrangement but is not always available, as it requires a special generator.

Construction of condensers. Condensers may be conveniently made up in a number of ways.

Leyden jars in sufficient quantity are satisfactory, though the writer has not found them nearly as convenient as other forms. The capacity of a leyden jar having 50 square inches of foil coating inside, and having a glass wall approximately three thirty-seconds of an inch thick is somewhere near 0.0005 microfarads.

Glass plates with tin-foil cemented on them, and placed in a rack, are effective but easily broken.

Sheets of metal between sheets of solid insulating material such as oiled cambric or oiled paper, either in or out of oil are quite satisfactory.* This type of condenser, though inferior in point of dielectric loss, is extremely compact, is easily constructed of materials readily obtained, and is quite robust. The leads are preferably brought out from each condenser plate separately, so that the capacity and insulation strength may be varied by connecting the plates in different combinations.

Tests of choke-coils. Although lightning-arrester choke-coils, and other forms of auxiliary apparatus accomplishing the same purpose, do not serve the same function as lightning-arresters, yet the impedance offered to the discharges from the line is of importance, since it is the function of the choke-coil to offer as large an impedance as practicable to such surges as may pass an arrester. Comparative tests of the impedance values of choke-coils are especially desirable at the present time, since there is very little data on the relative choking power of the more usual designs of such coils, and their relative merits are not easily determined otherwise. These tests do not involve very much difficulty in the making, and when made as comparative tests serve an important function.

The same apparatus and method of tests as described for testing the impedance of arresters to discharge, may be utilized in connection with two or more such coils in a series, one being a standard for purposes of comparison. The needle-gap should be taken on each of the two coils under the same or similar conditions, and a comparison of results will show the relative power of these coils. By this same means the insulation strength of the coil and the spacing of its leads can be tested.

POWER TO SUPPRESS THE GENERATOR ARC

General considerations. This all-essential feature of an arrester is unfortunately extremely hard to test and determine in the general case, since the difficulty of suppressing a generator arc increases with larger and larger currents and is multiplied many times when the generator circuit includes much inductance. With many arresters, tests made on anything less than a full-size plant cannot give a safe guide for judging the non-arcing power of an arrester, since only on such plants can the maximum generator current be obtained. Designs behaving perfectly satisfactorily in many laboratory tests on medium-size machines, or on large machines with limiting resistances, may very likely fail utterly to suppress the arc when placed upon regular commercial circuits. In a paper, presented concurrently herewith and supplementary to a paper by the writer read at the annual convention of the American Institute of Electrical Engineers in 1902 on the "Function of Shunt and Series Resistance in Lightning-Arresters," are shown some curves of the non-arcing power of multigap arresters on alternating-current circuits, which are the result of actual tests and show this fact in a very marked manner.

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*The capacity of a plate condenser may be calculated fairly closely from the formula: Capacity in microfarads = the area of one plate in square inches divided by the thickness of dielectric in inches $\times 2.25 \times$ the specific inductive capacity $\times 10^{-7}$. The specific inductive capacity of air is 1 and of solid dielectrics from 3.5 to 6.

This condition is not of an imaginative nature, since this very difficulty has occurred a great many times. It is very seldom that conditions are favorable for making such tests, as they require, except with an arrester inherently limiting the generator current, practically the exclusive use of a large generating plant; and, because short-circuits may be produced frequently, there is great danger of damage to the generating apparatus. It is of course true that lightning-arresters, themselves limiting the flow of current from the generator, need be tested on circuits only just large enough to supply, without material drop of potential, the current naturally taken by the arrester. In all cases it should be definitely determined that no more current would be supplied during the discharge were the generating capacity infinitely large, otherwise the test would not be trustworthy. Also, it is important that, where necessary, special inductance should be introduced into the circuit to represent any inductance which might be found in an actual power system; as, for example, the inductance of a transmission line. The presence of such inductance markedly increases the difficulty of suppressing the generator arc.

Speaking broadly, it may often be determined from general considerations whether an arrester will be non-arcing or not, in which case tests will be unnecessary. In practically all free-discharge, non-arcing arresters, the tests of non-arcing quality will cause destruction of the arrester and usually of several arresters. Considering more particularly the bearing of the various arrester types on tests of non-arcing power, the following should be noted:

a. A number of arresters utilize a free discharge path to earth, with means brought into action after the passage of the discharge for suppressing the arc. Such are the fuse-type arrester, the horn arrester, the magnetic-blow-out arrester, etc. The horn type is sometimes used in connection with series resistance or with a fuse, in which case it should not be classed as a horn arrester but as a resistance or fuse arrester.

The ability of these arresters to suppress the generator current then becomes a question of the ability of the fuse, the horn form, or the magnetic field to open the circuit. There seems to be no doubt of the ability of a properly constructed fuse, usually of an enclosed or explosive type, to open any circuit. Numerous tests have been made on this subject. There is a good deal of question as to the ability of horn arresters to open promptly very heavy currents. Magnetic-blow-out arresters are used only on low voltages where they have a very decided arc-opening power.

b. Arresters of the series resistance type. When the series resistance is very large, the maximum generator current will be low, and there will be no question as to the non-arcing character of the arrester.

When the series resistance is made as small as possible, as is usually the case in connection with the multigap shunt resistance arresters which are much used for high alternating pressures, the design of the arrester is usually somewhere near the lower limit of non-arcing power and tests will be of value. The factors determining the non-arcing power of multigap arresters, with or without shunt resistance, have been pretty thoroughly investigated. As a matter of fact, with a given inductance in the circuit, the number of gaps required to suppress the generator arc with a high-tension alternating-current circuit increases at a rate between the first and second power of the current. With increase in inductance in the circuit, it also rapidly increases with a given current.

c. The types of special material or special form arresters already referred to, including arresters of unknown method of operation, will be found generally to have characteristics intermediate between those of the two classes above mentioned, and very little can be inferred as to their non-arcing power aside from tests, unless the results of actual experience have been sufficient. Unfortunately, with special forms on high voltages, for reasons already explained, it is often very difficult to make adequate tests. For low voltages, alternating and direct-current, however, it is relatively easy to make tests, and they are often to be recommended, especially where claims are made for some unknown arrester which has not been widely and publicly used.

Description of test. The tests of non-arcing power are made by reproducing operating conditions; that is, connecting an arrester across a powerful supply circuit and passing a static discharge across the whole or a part of the arrester to initiate the generator arc. The generator capacity should in all cases be sufficient to supply, without material drop in voltage, all the current which the characteristics of the arrester will allow it to take. On this account, tests on horn and fuse-type arresters and other types not limiting the flow of generator current on discharge are rarely practicable. When made on smaller machines, or by limiting the current flow by resistance or otherwise, they are of little value.

The *inductance* corresponding to the maximum inductance to be expected in service, should be included in the generator circuit.

Source of static discharge. It is a very troublesome matter to obtain a satisfactory source of the static discharge. Where a Holtz or frictional machine is available, and the voltage is not too high for this machine to cause a discharge, it may be satisfactorily used. In most cases, however, it will be found more satisfactory to get the high-tension discharge from a transformer. An arrangement similar to that already described for testing the impedance offered to discharges by arresters, may be here utilized. In this case, a much smaller condenser may be used than for the above test, and the voltage need be only just high enough to cause the discharge. It is essential in such a test to avoid synchronism, that the source of discharge be not taken from the same supply as the generator, since, if the static waves have always the same relation to the waves of the generator, all conditions of practice would not be obtained. If special pains should be taken to adjust phase relations to give the discharge at the most severe point of the wave, the same source might be used, but this method is difficult and uncertain.

Evidently, in order to get the most unfavorable condition for suppressing the generator arc, the discharge should be passed over the arresters in the early part of the cycle of the generator wave, since this allows maximum of heating or other activity in the arrester before the first zero point.

The actual severity of the exciting static discharge seems to be unimportant in this work; a comparatively slight spark is entirely sufficient.

Protection of apparatus. It is necessary in practically all cases to protect the generator, by powerful choke-coils or static interrupters, from the strains produced by the static discharge utilized to jump the arrester. It is desirable as well, unless otherwise provided for, to protect the high-tension side of the charging transformer, by means of choke-coils or other apparatus, from a short-circuit due to the condenser discharge across its leads.

Timing the discharge. The production of the exciting spark at the proper time of the cycle may be accomplished by a small synchronous motor driven from the supply and arranged to close the circuit at the proper time, as described in papers by E. E. F. Creighton on " New Principles in the Design of Lightning-Arresters," read at the March meeting, 1907, and " Methods of Testing Protective Apparatus," read at the annual convention, 1906, or it may be accomplished by the swing-switch method already described, in which case a number of trials must be made with each setting of the apparatus to ensure the reaching of the worst condition, since the point within the cycle at which the discharge occurs is largely a matter of accident. From 20 to 50 trials should be made under each condition. This method is preferable to the synchronous-switch method, as so much dependence need not necessarily be placed on the accuracy of the operating mechanism. Oscillograph curves are here, of course, a great safeguard.

Auxiliary Apparatus. It is very desirable in tests of this sort to have an adjustable resistance controlling the flow of current from the generator, which can be cut out gradually until the maximum condition is reached. Such a resistance must be of a very robust and well-insulated character. It is also necessary to have in circuit an entirely reliable circuit-opener of some sort, such as an oil-switch or a fine-wire enclosed fuse. Either arrangement may be made satisfactory.

It is, of course, of interest and value to have oscillograph records of the currents and voltages of the tests, but as this involves a great deal of work in setting up the apparatus and is not wholly necessary, the oscillograms will often be omitted.

It should be noted in testing alternating-current multigap arresters utilizing shunt resistance, that, if when the static discharge is produced at the early part of the cycle, no current follows into shunted gaps; the discharge should be produced at a somewhat later point of the alternation, as this will be more favorable for the initial starting of current in the shunted gaps.

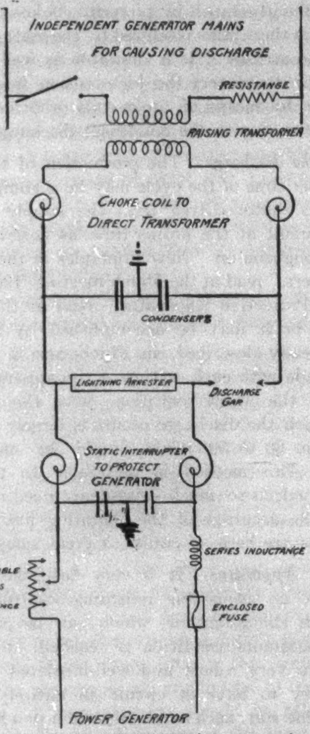
INDEPENDENT GENERATOR MAINS
FOR CAUSING DISCHARGE
RESISTANCE
RAISING TRANSFORMER
CHOKE COIL TO
DIRECT TRANSFORMER
CONDENSERS
LIGHTNING ARRESTER
DISCHARGE GAP
STATIC INTERRUPTER
TO PROTECT
GENERATOR
SERIES INDUCTANCE
ADJUSTABLE
SERIES
RESISTANCE
ENCLOSED
FUSE
POWER GENERATOR

FIG. 3—Diagram of circuits for testing non-arcing power of lightning-arrester

Thus, in the case of shunted gaps the most critical point of the cycle for the discharge is different from what it is in the case of plain series gaps.

One diagram of connections for testing the non-arcing power of arresters is shown in Fig. 3. This is capable of various modifications. Reference is suggested to the various papers above referred to by Mr. Creighton and the writer. The arrangement shown by Mr. Creighton is presumably satisfactory where applicable.

Attention is again called to the fact that except where arresters have an inherent faculty of limiting the flow of current, tests to be of value must be made upon high-capacity generators and circuits; they are then very troublesome to make and involve considerable danger to the generator and other apparatus connected to the test circuit, both from the heavy short-circuits and from static strains. Line choke-coils playing practically no part in the arc-suppressing power are not involved in this test.

Disturbance of operation. When the discharge of an arrester offers a free path for the flow of generator current, the result is the lowering of the line voltage to such an extent as to cause synchronous apparatus to drop out of step, and, in view of the heavy current taken by the arrester, the opening of the circuit-breakers or the blowing of fuses. This is a most serious matter in practical operation and has caused a great many shut-downs. These shut-downs are serious, as the whole system must be started again, including the synchronizing of generators, synchronous motors, and synchronous converters. The critical conditions evidently are the generator current taken during the discharge, and the length of time before its suppression; for example, a current strength which in one alternation would be insufficient to open a circuit-breaker might, if continued for a dozen alternations, cause this result. Arresters which sufficiently limit the generator current following the discharge will cause no disturbance; and arresters suppressing the generator current within an alternation or so will undoubtedly cause no trouble, however great this current. Arresters utilizing series resistance and drawing only a few times full-load current would not be expected to open breakers or throw out synchronous converters; fuse arresters utilizing a small wire-enclosed fuse which open the circuit very quickly are probably safe, but horn arresters and their equivalent will usually disturb the system.

Tests to determine whether or not a definite arrester will in general cause this trouble are impracticable, for the different settings of breakers, the different designs and loads of synchronous apparatus, together with the different location of discharges, will render a general determination out of the question. However, it may often be concluded from general considerations that an arrester cannot even take current enough to disturb the system, or that it is sure to take current enough to cause trouble.

Under specific sets of conditions, as at some particular plant, by selecting the most sensitive condition, it may be determined by trial whether an arrester discharge is likely to cause disturbance of the operation, by repeating the test just described for determining the non-arcing power of arresters. This will, however, usually be considerable of an undertaking and not worth while.

Capacity for frequent discharges. It goes without saying that every arrester should be able to withstand as many successive discharges as it may meet in actual service. Unfortunately, this condition is exceedingly variable and impossible of general determination. High-voltage arresters will presumably discharge much less frequently than will low-voltage arresters, as in the former minor disturbances will not be able to pass to the ground. Furthermore, on alternating-current circuits at least, discharges occurring at one part of a cycle are more severe than discharges occurring at another, which tends to relieve the arrester. Under the conditions in which tests for non-arcing power are feasible, tests to determine the capacity for frequent discharges may be made. The parts particularly subject to deterioration under these conditions are series and shunt resistance, magnet-coils, and the cylinders in multigap arresters.

On low-voltage circuits, direct and alternating, where working conditions are more easily reproduced, such tests are often feasible. On high-tension alternating-current circuits, however, they are not often worth while.

Tests for determining capacity for frequent discharges should be made as already described for determining the non-arcing power of arresters. A number of discharges should be produced in succession at intervals of some seconds, the exact number of repetitions and the intervals being determined according to the circumstances of the case.

Deterioration, etc. There are a number of other characteristics of great importance in the choice of arresters which, however, cannot readily be made a subject of test. Arresters should be robust; the resistances should be of a character not to corrode or otherwise deteriorate with time; they should be as simple as possible and the parts likely to deteriorate should be replaceable.

To require a renewal by hand after a discharge, before an arrester is ready for a second discharge is a serious handicap.

Conclusion. It is evident from the analysis of the advantages, disadvantages, and limitations of the various possible tests of lightning-protective apparatus, that certain tests are of great value in connection with certain types of arresters, but not with all types, and that some of the tests are difficult and awkward to make. It would thus seem that tests should be introduced into the standardization rules cautiously and gradually.

On the other hand, there will be a great advantage in many cases in testing lightning-arrester apparatus; for example, a ready means of correctly sizing up the numerous low-voltage arresters, especially railway arresters, which appear from time to time is desirable. Furthermore, the fact that certain tests have the stamp of approval of the Institute will do much to cause designers to put their apparatus in condition to meet the tests even if the tests be so inconvenient as rarely or never to be imposed. Again, a careful consideration of a properly chosen set of rules will help materially to give to electrical engineers who have not paid much attention to static phenomena a clear idea of the fundamental conditions to be kept in mind.

The following tests are suggested for general consideration as suitable for the approval of the Institute:

1. In all lightning-arrester design, the insulation strength should be required to stand the abrupt application of the discharge of a condenser of at least 0.01 microfarad capacity, charged to a potential three times normal arrester potential, and not less than 50,000 volts, without sparking between parts or to ground. Where it is inconvenient to get a discharge of this severity, arresters, alternating-current and direct-current, for not over 3,000 volt lines can be roughly tested with a smaller capacity or lower potential, but no tests with capacity less than 0.0025 microfarads or voltage less than 30,000 should be relied upon.

2. Breakdown voltages at normal frequency should be determined in all cases, following, where applicable, all the requirements laid down in the standardization rules for the testing of insulation strength.

On voltages of 40,000 and higher, the test should if possible be made with the arrester installed in position, and in any case with the same relation to surrounding grounded or charged objects as it is to have in final installation.

3. Where general considerations are not sufficient to determine the amount of impedance offered to a discharge, comparative tests between arresters may be made by noting the needle-gap equivalents of two or more arresters, by passing across the arresters separately or in series the discharge of a condenser of a few hundredths microfarad capacity charged to a potential not less than 50,000 volts, or less than three times the normal voltage of the arrester. This test will be of relatively little value with an arrester including series resistance of equivalent characteristic, since the test will show simply the voltage of the discharge in each case. Such comparative tests may be made with smaller capacities and lower voltages, though they will not be as trustworthy.

The impedance offered the discharge should be measured by a needle-point spark-gap in shunt to the terminals of the arrester, and set to take half the discharges. The needle-point gap should be shielded by metal, if near the main discharge-gap.

4. Where general considerations are not sufficient to determine the non-arcing power of an arrester, a test may be made by passing sparks over the arrester when connected to a source of electromotive force of sufficient power to supply, without dropping its potential, all the current which the arrester will take. In no case need a generator power, greater than the maximum to which the arrester is to be subjected, be used. In all cases the maximum series inductance to be found in service must be included in the generator circuit.

With arresters which offer no impedance to the discharge, such as the horn type, the fuse arrester, and the multigap arrester without series resistance, etc., reliable tests can be made only on the maximum generator power to which the arresters are to be exposed.

Non-arcing tests are difficult and dangerous for apparatus in all cases except where the generator current is strictly limited. The testing apparatus should be protected both from the static discharge and from the effects of the short-circuits.

5. Endurance tests may be made in the same manner as tests of non-arcing power. The discharges should be repeated at intervals of some seconds. The exact interval and continuance of test must be a matter of judgment in each individual case.

This test is especially useful and feasible in connection with low-voltage arresters, such as direct-current railway types.

6. In addition to the behavior of arresters under the above tests, other features should receive consideration; for example, the disturbance of normal operation caused by a discharge, robustness and permanency, simplicity, whether or not replacement is required after a discharge, etc.

As the only final test of a lightning arrester is actual experience extending over considerable time and repeated in many places under different conditions, no general conclusions should be drawn from short-time trials. Such a determination usually requiring years, the considerations and tests enumerated above are of great practical value in determining the relative merits of different types of apparatus.

APPENDIX I

The reasons for concluding that very high frequencies do not have to be considered in the protection of commercial lines may well be somewhat elaborated. Since the quality which renders the discharge of a static surge of a given magnitude exceptionally difficult is very great abruptness, that is, very sudden arrival of charge, we should here consider not strictly the frequency of discharges, but rather the form of the initial wave-front. Strictly speaking, the term frequency is applicable only where there is an oscillating current or potential. The term abruptness of discharge is more generally applicable. This abruptness of charging depends upon the time required for a given point to pass from normal to a given abnormal potential. This time is especially short with very high charging potential and low inductance in the charging path.

Every lightning-arrester has some capacity; so have the line wire outlets, insulator tie-wires, and every conductor or patrol conductor connected with the line. Consequently, to raise the potential at the lightning-arrester discharge-gap to a dangerous point, a certain amount of charge is required. Since this charge is transmitted to the arrester by the line wires, there will be a minimum length of wire which will be sufficient to store charge enough to cause this rise of potential. Such a value as ten feet of line wire would seem to be very conservative as the minimum limit of capacity which could store sufficient energy to produce material strain. The capacity of two transmission wires, 10 feet long, is approximately 1.5×10^{-5} microfarads. It is hard to imagine a possible case in which such a length of wire can be abruptly charged through a path having less inductance than that of 5 feet of such a transmission wire, which will be about 4×10^{-6} henrys. Consequently, since the time of the complete discharge period of a condenser through an inductance is = $2\pi\sqrt{CL}$, in which expression capacity may be farads and inductance henrys, the frequency of discharge of this condenser through this inductance will be approximately 20,000,000, per second. This is presumably the maximum frequency which need ever be considered in a transmission line, and even this is probably too high.

The only conclusion to be drawn from the above is that in a general way we may neglect the effects of any disturbances having a higher frequency than a few million periods per second. It is of course true, however, that, since the inductance and capacity of the transmission line is distributed, the above formula cannot be applied directly thereto. The true results will not differ radically from those derived by the assumptions made. As further reducing the probability of harmful effects being produced by very high frequencies, it should be noted that every irregularity of form, every insulated tie-wire, every branch connection of any kind, or leakage into air over insulators, and any current set up in other conductors, tend, especially with very high frequency, further to break up an advancing wave and also to dissipate its energy.

A few outer turns of a transformer winding have a large enough electrostatic capacity to be of very material moment in keeping down potential rises from very high-frequency discharges; for example, consider the outside layer of a transformer coil, which may be taken as three-fourths of an inch wide. Such a transformer as would be connected to a high-tension transmission line would have perhaps a mean length of turn of six feet, giving an exposed area on the top and edges of the first layer of about 75 square inches. The mean distance of such a layer from grounded objects, or objects acting as though grounded for the necessary brief instant of time, would be not far from two inches in a high-tension transformer. The specific inductive capacity of the insulating material is at least three, giving a capacity of 2.5×10^{-5} microfarads. This is equal to about 10 or 15 feet of transmission line. This estimate is probably very much too low, since, if the frequency is high enough so that only the first layer is affected, the next layer or two will act as though grounded and will increase the capacity of the first layer ten or twenty times. In other words, as far as the protection of transformers from ground is concerned, there must be a very considerable volume of charge at high potential passed into the winding before a jump to ground will result. The immediate leads of the transformer are presumably protected by this capacity, and indeed they add some capacity of their own. On the other hand, station wiring gets no benefit therefrom, when the transformers are disconnected.

In general, then, in view of the fact that there must be in all commercial lines at or near the arrester a certain minimum capacity, which in a general way for the purpose of discussion may be assumed as at least equal to 10 or 15 feet of transmission line, no disturbances involving a materially less capacity can cause serious damage. Consequently, no higher frequencies than can occur in connection with the minimum capacity need be considered in lightning-arrester work. This frequency will probably not exceed a few million per second. The same general line of reasoning applies to low-tension line wires. With these, the values of electrostatic capacity and all leakage factors are greater than for high-tension lines.

APPENDIX II

There are certain limitations in the severity and possible forms of discharges from commercial transmission lines which are important in considering the impedance offered to discharges by various designs of arresters.

The exact maximum electrostatic capacity that can ever, in a commercial circuit, be so located as to be abruptly discharged through a lightning-arrester is very difficult to estimate accurately. The conditions of the test recommended for measuring the impedance to discharge of an arrester are very severe, more severe probably than are likely to be met with in practice, for the following reason: In the test recommended, the total charge of the condenser is passed directly against the arrester through only the impedance of a few feet of wiring. In an actual transmission plant, there can be connected so closely to the discharge path of the arrester only 100 or 200 feet of line and at most a few high-tension transformers. This capacity will be increased somewhat by tie-wires, insulator surfaces, bushings, outlets, etc. Taking these things together, however, the capacity within a few feet's discharge of the arrester will fall far short of a hundredth of a microfarad. On the other hand, there may be in the immediate neighborhood a capacity considerably larger than this amount. Such excess of capacity, however, must discharge through some tens or hundreds of feet of transmission line, which will very much reduce its severity on the arrester discharge.

Neglecting the concentrated capacity closely adjacent to the arrester, which has already been described as limited to a quantity presumably much less than a hundredth of a microfarad, the current passing from the transmission line proper may be likened to the discharge of water from a long uniform trough. If such a trough filled with water be allowed to discharge by the opening of one end, there will be a sudden rush as the water accumulated at this end passes out, but this rush will be immediately followed by a steady stream of water of practically uniform section while the trough empties itself. The rate of flow at the outlet once established on this steady basis will not change materially until after the "falling" wave which passes backward reaches the end of the trough and is reflected again toward the outlet. Similarly, with the transmission line; assuming it to be charged to a very high potential and the discharge to start at one end over an arrester, there will be an initial rush of the charge stored in the immediate neighborhood of the arrester (this would include that stored in bushings, transformers, branch wires, etc.), but when once this charge, which is limited in amount by the conditions already stated, has once passed, further charge will flow out of the line through the arrester at a more or less uniform rate which is determined by the relative inductance and capacity of the transmission line, but which thus produces no steadily increasing demand on the discharge capacity of the arrester. If, instead of the whole transmission line being charged to this high potential, the disturbance be one of high frequency, this is equivalent simply to shortening the trough of water or the transmission line and will relieve the arrester so much the more easily.

Evidently, an arrester which discharges somewhat slowly will have a harder task to perform, since the distance of the farthest charge which can discharge directly through the arrester on the initial breakdown without material opposition from line inductance will extend to a greater distance; for example, an arrester with series resistance will be more likely to receive an absolute direct discharge from as great a capacity as a hundredth of a microfarad, than will a fuse-type arrester.

Even in the severe condition in which a direct stroke of lightning reaches the transmission wire at 1000 feet from the arrester, a similar limitation exists, since all charge. above that necessary to bring the potential of the line wire to the point of breaking to earth from the line over insulators, is discharged directly to ground, and, as before, we have only the charge on the transmission wire to be discharged over the arrester. There is, however, one exception; namely, when the lightning stroke is continuous for some relatively considerable period of time, in which there will be a transter of current over the line wire through the arrester to ground, not in the form of a wave or surge (relying on the distributed inductance capacity for its transmission), but as an ordinary current in a conductor governed by the impedance of the line. In this case, the effect of the inductance of the line and the arrester discharge path will soon disappear leaving the resistance of the line and of the arrester to withstand the voltage of the discharge. How common such a condition is at the present time is a mere matter of speculation.

Mr. R. P. Jackson, in his paper of last December on "Recent Investigation of Lightning Protective Apparatus," called attention to the fact that there is a limit to the amount of discharge current which can be obtained from the electrostatic capacity of a transmission wire at a definite voltage regardless of the length of the line.

It may be thus concluded that there is a surprisingly low limit to the severity of the discharge which an arrester can be called upon to discharge from a transmission line, and it is the opinion of the writer that the "several hundredths of a microfarad" recommended by this paper in the test for measuring the impedance offered to discharges is justifiable principally to give a margin of safety and to provide in the most practical available manner for the fact that the actual arrester will have to discharge lines charged to a considerably higher potential than that of the test, which, of course, renders the condition more severe.

The writer wishes to take this opportunity to make the plea that it would be far better in discussing lightning-arrester problems to avoid expatiating upon what we do not know and cannot know about lightning, and statements to the effect that the conditions are infinitely various and incomprehensible; and to make a serious effort to determine and explain such limitations and facts as we may know and can determine from known laws and from experience. If this be done, the subject would lose most of its mystery; operating engineers would be able coherently and intelligently to observe and judge by what they see, and the advancement of lightning-protection would be very much facilitated.

APPENDIX III

Various papers bearing upon the reaction of lightning on transmission lines, and of the various characteristics and performances of lightning-arresters for light and power circuits have appeared from time to time in the Transactions and Proceedings of the American Institute of Electrical Engineers. For convenience they are here enumerated.

"Lightning Arresters and the Photographic Study of Self-induction." E. G. Acheson. Vol. VI, 1889.

"Some Possible Modifications in the Methods of Protecting Buildings from Lightning." N. D. C. Hodges. Vol. VIII, 1891.

"Lightning Arresters and the Discovery of Non-arcing Metals." Alex. J. Wurts. Vol. IX, 1892.

"Discriminating Lightning Arresters and Recent Progress in Means for Protection against Lightning." Alex. J. Wurts. Vol. XI, 1894.

"Theoretical Investigation of Some Oscillations of Extremely High Potential in Alternating-High-Potential Transmissions." Chas. P. Steinmetz. Vol. XVIII, 1901.

"Static Strains in High-Tension Circuits and the Protection of Apparatus." Percy H. Thomas. Vol. XIX, 1902.

"The Function of Shunt and Series Resistance in Lightning Arresters." Percy H. Thomas. Vol. XIX, 1902.

"The Grounded Wire as a Protection against Lightning." Ralph D. Mershon. Vol. XXII, 1903.

"Safeguards and Regulations in Operation of Overhead Distributing Systems." W. C. L. Eglin. Vol. XXII, 1903.

"Protection of Cables from Arcs Due to the Failure of Adjacent Cables." W. G. Carlton. Vol. XXIII, 1904.

"The Protection of High Pressure Transmission Lines from Static Discharges." H. C. Wirt. Vol. XXIII, 1904.

"High-Power Surges in Electric Distribution Systems of Great Magnitude." Chas. P. Steinmetz. Vol. XXIV, 1905.

"An Experimental Study of the Rise of Potential in Commercial Transmission Lines Due to Static Disturbances Caused by Switching, Grounding, etc." Percy H. Thomas. Vol. XXIV, 1905.

"Some Experiences with Lightning Protective Apparatus." Julian C. Smith. Vol. XXIV, 1905.

"Notes on Lightning Arresters on Italian High-tension Transmission Lines." Philip Torchio. Vol. XXIV, 1905.

"Performance of Lightning Arresters on Transmission Lines." N. J. Neall. Vol. XXIV, 1905.

"Some Experiences with Lightning and Static Strains on a 33,000-Volt Transmission System." Farley Osgood. Vol. XXV, 1906.

"Methods of Testing Protective Apparatus." E. E. F. Creighton. Vol. XXV, 1906.

"Protective Apparatus for Lightning and Static Strains." H. C. Wirt. Vol. XXV, 1906.

"Recent Investigation of Lightning Protective Apparatus." R. P. Jackson. Vol. XXV, 1906.

"Lightning Phenomena in Electric Circuits." Chas. P. Steinmetz. Vol. XXVI, 1907.

"Protection against Lightning, and the Multigap Lightning Arrester." D. B. Rushmore and D. Dubois. Vol. XXVI, 1907.

"New Principles in the Design of Lightning Arresters." E. E. F. Creighton. Vol. XXVI, 1907.

"Notes on Hydroelectric Plant Organization and Operation." Farley Osgood. Vol. XXVI, 1907.

"Potential Stresses as Affected by Overhead Conductors." R. P. Jackson. Vol. XXVI, 1907.

CURVES OF THE NON-ARCING POWER OF MULTIGAP LIGHTNING-ARRESTERS AND THE SHUNTING POWER OF OHMIC RESISTANCE.

These curves and descriptive data are supplementary to a paper by the writer read before the annual convention of the American Institute of Electrical Engineers in June, 1902, and entitled, "The Function of Shunt and Series Resistance in Lightning Arresters." In the original paper, the principal conditions governing the non-arcing power of multigap arresters on constant potential alternating-current circuits were discussed. The results from which these conditions were determined had been plotted in the form of a series of curves which were not at that time published. These curves, which are the result of a very large number of tests at several voltages and on various circuits, are here reproduced.

These curves although not to be interpreted with minute accuracy, which would be out of the question in work of this character, are believed to be thoroughly reliable under general commercial conditions. They are, of course, not of absolutely general applicability, since, for example, practically all the tests were made with gaps at or near one-thirty-second of an inch, and would presumably not hold closely for widely different lengths of gap; also, the curve showing the shunting power of ohmic resistance is plotted on the assumption that the number of series and shunt-gaps is approximately the same. There are, however, so far as the writer is aware, no limitations such as have just been mentioned, which are not clearly stated either in connection with the curves themselves or in the original paper referred to.

It is expected that these curves will be of interest in connection with the papers, to be presented concurrently herewith, on the subject of the testing of lightning-arresters.

The general method of making these tests is fully described in the original paper, and consisted in passing static sparks repeatedly, at instants of time determined by chance, across a series of gaps which were connected to a generating system including resistance and inductance where necessary, so that a known current would flow through a known inductance upon short-circuit. The number of gaps was varied in repeated trials until it was determined how many would always suppress the arc following a static discharge, and also what was the greatest number of gaps which could be made to fail. Similarly with the shunting power of resistance. With known conditions of short-circuit current from the generator, static discharges were passed repeatedly until both the condition of failure and the condition of minimum successful operation were obtained.

The tests on 12,500- and 25,000-volt circuits were made on one or two generators of 5,000 h.p. capacity and having an exceptionally large flywheel capacity. It will be noted in the curves that free short-circuit currents were not taken from the generators. The currents actually used were, however, increased up to the point where burning of the cylinders became a limiting factor for commercial work. It is obvious from the form of the curves that larger currents flowing from the generator would greatly reduce the non-arcing power of the gaps and ultimately eliminate it.

It may be stated that a line of lightning-arresters adapted to all voltages from 2,500 to 50,000 has been designed from these curves. In some five or six years of operation, so far as the writer knows, they have never shown any failure to suppress the generator arc. In a very few instances, where by some accidental means a portion of the gaps has been cut out or a part of the resistance short-circuited, trouble has occurred, but this cannot be considered a failure of the arrester to be non-arcing.

Fig. 1 shows a number of one-thirty-second-of-an-inch gaps necessary to suppress the generator arc under the worst condition of static discharge with different initial short-circuit amperes, with different amounts of inductance in the generator circuit, and applies to circuits of 2,500 volts, 3,000 alternations. Each curve is for a definite inductance.

On 2,500-volt circuits, the non-arcing power is nearly inversely proportional to the initial current up to 500 or 600 amperes, with a low inductance.

Fig. 2 shows similar curves fo a 4,800-volt circuit, both at 3,000 and 7,200 alternations with various inductances.

On 4,800-volt circuits, the non-arcing power is still nearly inversely proportional to the initial current, especially with low values of inductance. The increase of the inductance makes an enormous decrease of non-arcing power.

Fig. 3 shows similar curves for 12,500-volt circuits, at 3,000 alternations. It should be noted in this figure that the very high values of inductance cause an enormous decrease in the arc-suppressing power of the cylinders. This shows how little can be determined as to the non-arcing power of a given arrester arrangement without a knowledge of the inductance in the circuit. It will also be noted in this figure that in general the curves bend up more sharply than before, showing that the

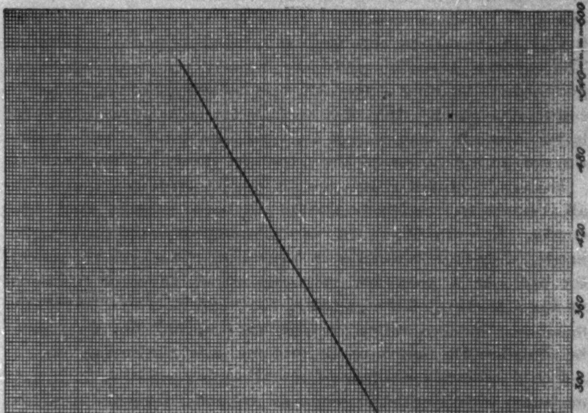

FIG. 1—Number of gaps necessary to suppress the generator arc with various initial short-circuit currents for different values of inductance in circuit, 2,500 volts, 3,000 alternations

high tension brings in a condition which is very exacting on the arc-suppressing power of the arresters.

On 12,500-volt circuits, the effect of the usual amounts of inductance found in commercial circuits becomes more important, and the non-arcing power drops and begins to decrease more rapidly than the initial current increases.

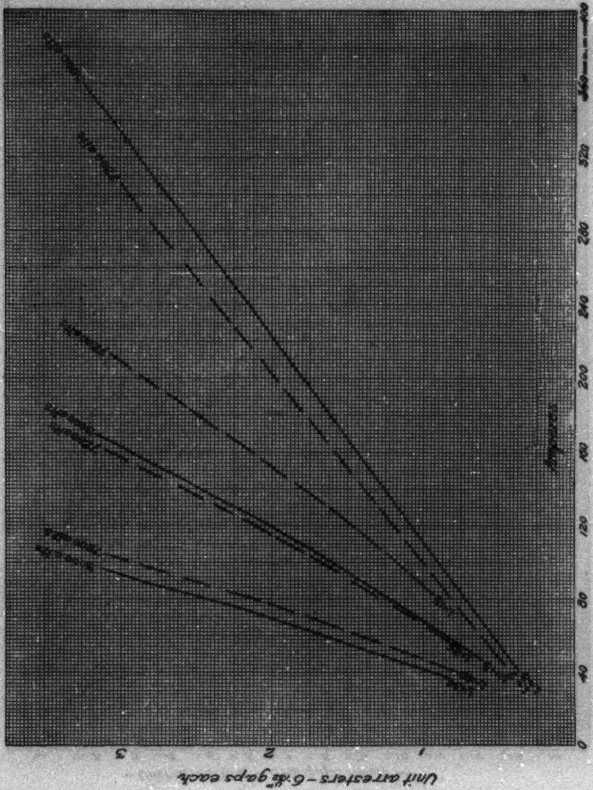

FIG. 2—Number of gaps necessary to suppress the generator arc with various initial short-circuit currents for different values of inductance in circuit, 4,800 volts, 3,000 and 7,200 alternations

Fig. 4 is similar to Fig. 3, except that the curves are for 25,000 volts and 3,000 alternations. In this figure, the tendency of the curves to bend upward is much more marked than in Fig. 3. In other words, the limitation of the initial short-circuit current is much more necessary in high-tension circuits than in low-tension circuits.

On 25,000-volt circuits the non-arcing power drops still lower on account of the predominance of the inductance of the circuit, and becomes nearly inversely proportional to the square of the initial current. The necessity of some resistance in such a circuit is very evident.

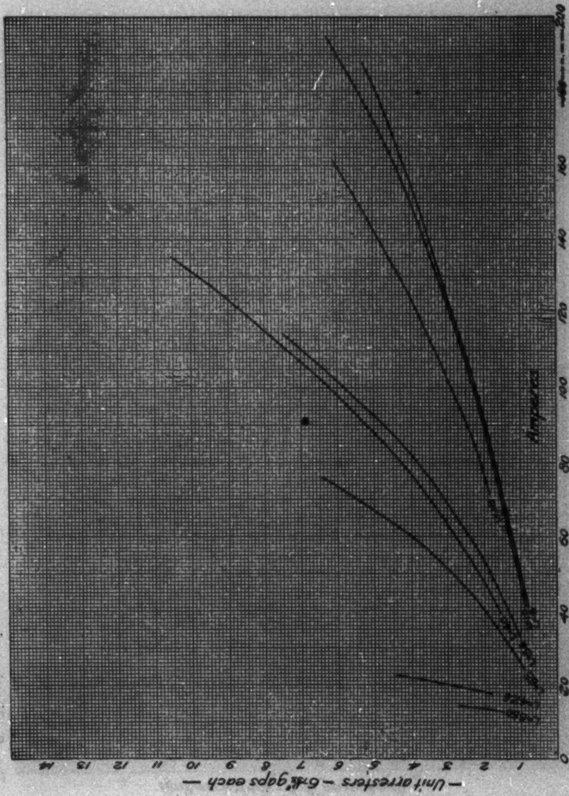

FIG. 3—Number of gaps necessary to suppress the generator arc with various initial short-circuit currents for different values of inductance in circuit, 12.500 volts, 3,000 alternations

Fig. 5 shows for different initial short-circuit currents in the series gaps of a combination of series and shunted gaps with shunt resistance, the number of ohms per shunted gap which will

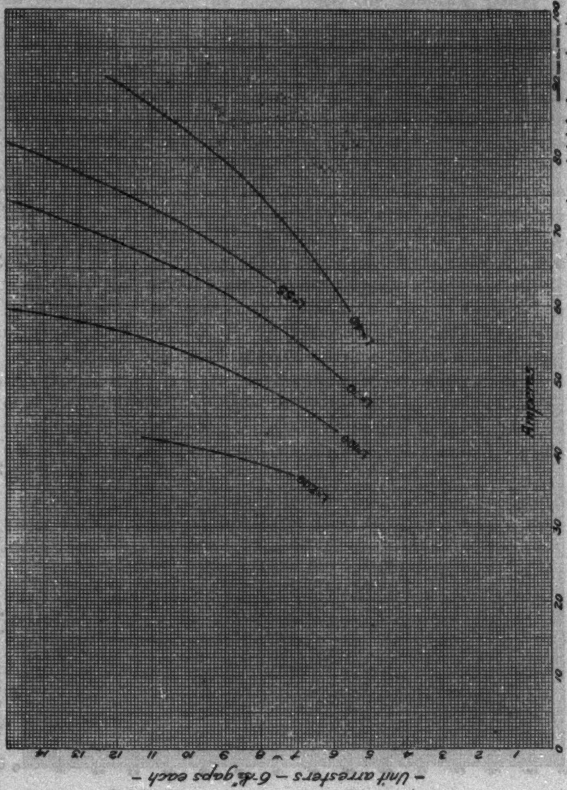

Fig. 4—Number of gaps necessary to suppress the generator arc with various initial short-circuit currents for different values of inductance in circuit, 25,000 volts, 3,000 alternations

just cause a dropping out of the arc in the shunted gaps. It will be noted that this value varies enormously with the initial short-circuit current, and that, for currents over perhaps 200 amperes, there is little or no shunting power for any useful value of shunt resistance. The gaps are as before one thirty-second of an inch, between Wurts's non-arcing metal knurled cylinders. The number of shunted gaps is always equal to the number of series gaps.

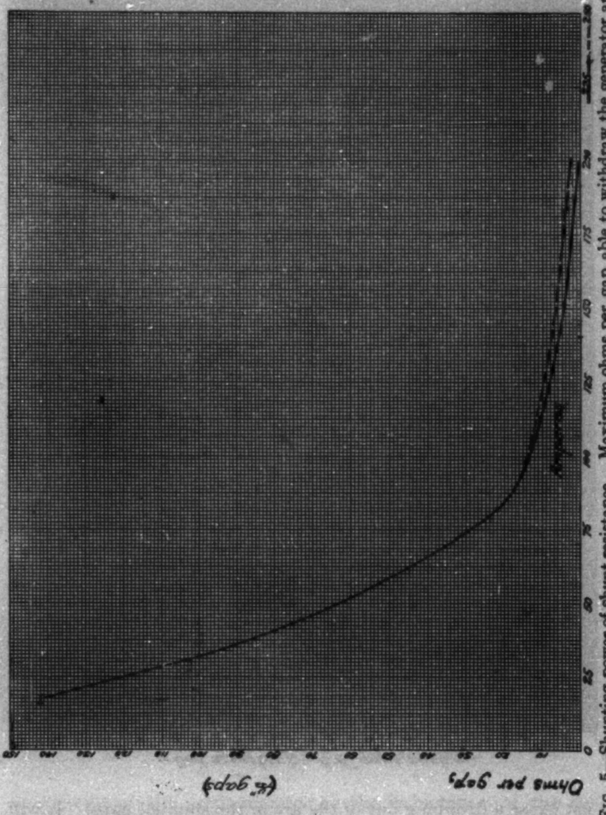

FIG. 5—Shunting power of shunt resistance. Maximum ohms per gap able to withdraw the generator arc from the shunted gaps with various initial short-circuit currents. Number of series gaps equals number of shunted gaps

For instance, with 25 amperes initial current a resistance of 120 ohms will just withdraw the current for the shunted gaps while with 175 amperes only from 2 to 5 ohms may be used, according to conditions.

The value of a given number of ohms per gap with a given short-circuit current is not entirely independent of the total voltage on the circuit of the inductance, etc., but is affected by these characteristics only to a minor degree. With high currents on low voltages, such as 2,500 volts, the shunting power is somewhat higher than with the higher voltages.

In estimates of the non-arcing power of arrester arrangements on various circuits, the initial short-circuit current is the dominating factor and the method of calculation becomes of importance. In these curves this current is calculated from the generated voltage of the supply, taking into account the total ohmic resistance in circuit, including rheostats, lines, and armature windings, the inductance of all coils introduced, the inductance of the line and of the armature, together with the estimated field reaction of the current in each case. It is assumed that the resistance of the arresters during discharge was practically zero. This method is not absolutely accurate, partly because the gaps have some resistance, partly because an accurate determination of the armature impedance and field reaction of the generator is difficult to make, and for other reasons. But this method does give values of current dependent upon the essential determining factors and is undoubtedly sufficiently accurate for all practical purposes. Of course, in using the data of the curves for other circuits, calculations should be made according to the same methods.

Reference to the writer's original paper on this subject is suggested for a description of the method of design of a non-arcing arrester for a given system from the basis of these curves.

A discussion of multiple shunt resistance will be found in papers by E. E. F. Creighton and by D. B. Rushmore and D. Dubois in Vol. XXVI of the TRANSACTIONS of the American Institute of Electrical Engineers, 1907.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 25, 1907.

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A PROPOSED LIGHTNING-ARRESTER TEST

BY N. J. NEALL

It is generally recognized that the worst disturbances to an electrical transmission system from lightning are due to the unbalancing of the circuit-elements after the passage of the initial lightning charge to ground.

In the development of lightning-arresters, provision must be made not only to discharge freely any atmospheric disturbances which take place near by, but to prevent as far as possible any short-circuit on the system which might thereby arise, should two legs of the line be simultaneously discharged. From this it follows that lightning-arresters, in the very act of relieving the line, introduce other conditions of potentially great destructiveness, such as short-circuits, sudden grounds, and oscillations.

Since it is impossible to predict where any given lightning disturbance will arise on a transmission line, the assumption is made here that this is ordinarily of no consequence, if it is not at the lightning protective apparatus. Any source of disturbance other than lightning which causes the lightning-arresters to operate may, however, properly be included here.

Fig. 1 shows the elements of the test. A spark from an induction-coil is made to pass over all the gaps of the lightning-arresters under test. This forms a bridge for either a short-circuit by line current (provided two legs of the line are simultaneously discharged) or for the passage of charging current from the stored capacity of the system, as the case may be.

The apparatus required consists of an induction-coil operated from several cells of a storage-battery by means of a mechanical vibrator. A small switch in series therewith enables the discharge to be controlled at will. A condenser is placed in series with each terminal of the induction-coil, the one being grounded and the other being led through spark-gaps to such a point of the series of the lightning-arrester gaps that the spark from the coil will divide and pass over them simultaneously in the direction of line and ground respectively.

Special gaps should be inserted in the induction-coil spark-circuit before connecting to the arrester under test to prevent a decrease in insulation strength to ground of the arrester itself.*

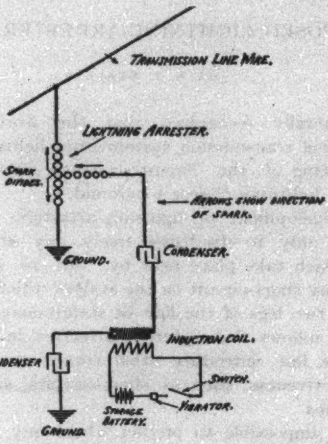
TRANSMISSION LINE WIRE.
LIGHTNING ARRESTER.
SPARK DIVIDES.
ARROWS SHOW DIRECTION OF SPARK.
GROUND.
CONDENSER.
INDUCTION COIL.
CONDENSER
SWITCH.
VIBRATOR.
STORAGE BATTERY.
GROUND.

FIG. 1.
SHOWS PRINCIPLE OF TEST.

Figs. 2, 3, 4 and 5 are self-explanatory.

It will be seen from the diagrams that the required insulation strength of the condensers, thus used in testing any polyphase system, is only half the nominal voltage between legs, for two condensers are always in series. Thus, for a test of a 50,000-volt line only 25,000-volt condensers are required.

With the exception of several laboratory tests, made first in

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*See Ingram, *Elec. Journal* Vol. IV, No. 4.

Minneapolis in September, 1906, on a 2300-volt circuit to prove the elements of the method, no trials have been made of this method on transmission lines. There is no apparent reason why it should not be used, save that, when the possibilities of the method are realized, most transmission operators will undoubtedly be afraid to try it lest it may demonstrate itself too successfully.

There are undoubtedly plants in this country, and perhaps abroad, whose operators would be glad to avail themselves of any such method of generating their own "lightning"—to employ a late application of this term—and the ideas contained herein are therefore presented with the hope that they may pave the way to increased knowledge of lightning disturbances and protection against them.

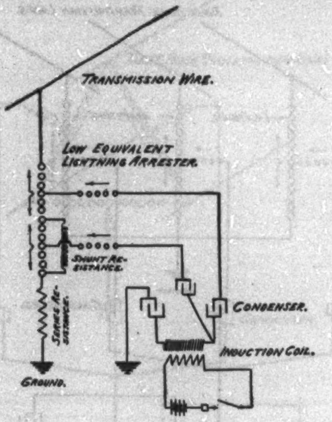
TRANSMISSION WIRE.
LOW EQUIVALENT LIGHTNING ARRESTER.
SHUNT RESISTANCE.
SERIES RESISTANCE.
CONDENSER.
INDUCTION COIL.
GROUND.

FIG. 2.

SHOWS SPECIAL APPLICATION OF PRINCIPLE TO LOW EQUIVALENT LIGHTNING ARRESTER FOR INITIAL DISCHARGE OVER ALL GAPS.

The following ideas have been suggested in this connection:

1. The apparatus must be adjusted in size and connection to individual requirements.

2. The effect of a disturbance can be measured positively by

the simultaneous use of tell-tale papers at all known points where discharges take place to ground.

3. The tests may be varied to suit any requirements; namely, short-circuits, grounding, phase to phase, etc.; and may be made simultaneously at extreme points of a line with duplicate test sets, if desired.

The following characteristics have been noted, and should be allowed for:

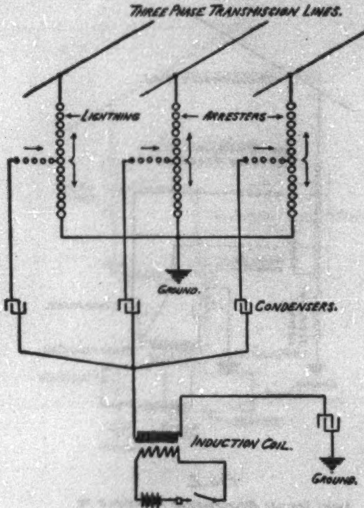

FIG. 3.

SHOWS METHOD OF CONNECTION FOR TESTING LIGHTNING ARRESTER GROUPS ON THREE PHASE SYSTEMS.

1. The coil must give a fat spark of considerable length. Such a coil as is used in wireless telegraphy is well suited to this.

2. The condensers need not be of great capacity. They may be of heavy glass coated with tin-foil and immersed in oil in stone jars.

3. There is apparently a definite limit to the number of gaps over which line voltage will break simultaneously with a given

static discharge. This has been noted in several cases and is quite marked. Any increase in the number of gaps, while apparently not affecting the spark, will prevent the arc.

4. Cells of storage battery permit the set to become portable, and thus enable field tests easily to be made.

5. The apparatus may be made quite rugged. In case of high voltage, the exciting-circuit knife-switch may be opened and closed by an insulating handle to protect the operator against possible break-down of insulation between line and ground.

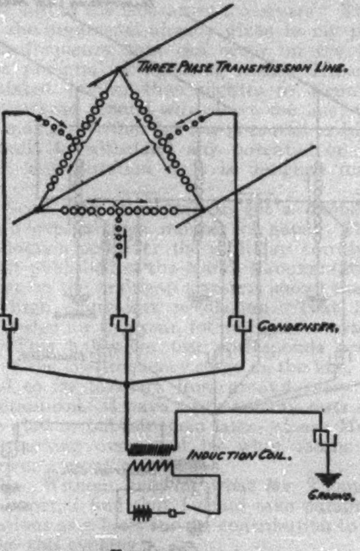

FIG. 4.

SHOWS A SUGGESTED METHOD OF TESTING PHASE TO PHASE.

6. The advantage in this method lies in its readiness for operation when required, its simplicity, and the fact that the induction-coil spark does not coat the cylinders or gaps with any metallic fumes.

7. It may be used for any lightning protective apparatus consisting of air-gaps between line and ground.

8. It is a method of as great value to the operator of the line as it is to the manufacturer of lightning-arresters, because it gives him the best possible method of determining how successful the lightning apparatus is in meeting the demands which he deliberately produces.

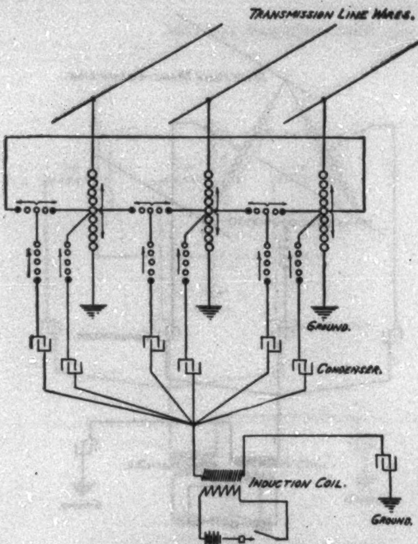

Fig. 5.

Shows a Suggested Method of Testing the Multiplex Principle on a Three Phase System.

9. Its intrinsic value rests on the importance of knowing as far as possible how great these disturbances may be, how efficient any given system of protective apparatus is to handle them, and of discovering to what degree any given transmission system contains in itself elements of length, arrangement, and character of apparatus tending to prolong or increase the disturbances once initiated.

DISCUSSION ON "LIGHTNING-ARRESTERS", AT NIAGARA FALLS, N. Y., JUNE 25, 1907

E. E. F. Creighton: I agree with Mr. Thomas on the main features of his paper, but disagree in regard to a few minor clauses, relating particularly to the equivalent spark gap. I wish to express my appreciation of the work he has done in the latter part of his paper in determining the number of gaps to obtain non-arcing conditions. I think that Mr. Thomas' test is more favorable to the arrester than it should be, for we can not make the test in the laboratory too severe. This statement is based on the arguments already given in my paper, on the variations in frequency that can occur on the line and the variations in potential of lightning itself. These factors can not be regulated further than slightly to diminish them by putting an overhead ground-wire above the line; therefore any arrester, no matter whether for low-potential or high potential, should be built to withstand any potential or frequency of lighting, and any duration if it is designed for continuous lightning.

Has Mr. Neall ever attempted to get a discharge from an induction coil over a large number of gaps? This discharge from the induction coil over the multigap corresponds to the half-wave test published in the March PROCEEDINGS 1906. The half-wave test on the multigap arresters shows that it gives an exceedingly high equivalent needle-gap. That has been the basis of our design for this year, for multigap arresters, to reduce this effect. This half-wave test corresponds presumably to the portion of the low-frequency surge on the line, and we have been enabled so far to spark from ground every few minutes by the induction coil. I have a great many tests of that kind, and shall be glad to publish them later. I ask Mr. Neall if he assumed a sparking over, and by what means he has been able to get over a great many gaps.

N. J. Neall: Without knowing what Mr. Thomas would set forth in his paper, I find that I could take paragraph 4 of his recommendations as a basis for the contribution to the Institute which I make this evening.

It is safe to say that the commercial testing of lightning-arresters to-day by the manufacturers is not carried much beyond 2500 volts in the factories, or above 25,000 volts in practice. The long term of years during which 25,000-volt lightning-arresters have now been in service has enabled arresters up to this voltage to become fairly satisfactory. But for voltages above this it is perfectly safe to assert that no manufacturing company to-day could make any such tests on lightning-arresters as have been stipulated by Professor Creighton and Mr. Thomas. One of the reasons for this is the large apparatus required, its costliness, and the difficulty of placing it in the factory, where it would hold up considerable work going through for customers.

It was for this reason that last year the method which I have proposed was devised in order that a collection of various well-known forms of lightning protective apparatus for station and for line service might be given a service test to determine their true merits. The principle of the test consists in passing a static discharge over the gaps of the lightning-arrester in such a way as to form a path for either a passage to ground of the stored capacity of the system or for such short-circuits as may be desired.

Those of us who are familiar with the practices of wireless telegraphy will recognize in the method a form which has been employed in that connection, but until I discussed the proposed test with Professor Reginald Fessenden in another connection, I was not aware that such was the case. I believe, however, that the application in this instance is original with me.

I would lay particular emphasis upon the opportunity which this test will now give the operator as well as the manufacturer to test out the arresters in practice, and for this reason I cannot too heartily urge the cooperation of the manufacturer and the operator to the end that more positive information be obtained as to lightning protective apparatus operation.

Chas. P. Steinmetz: Professor Creighton's paper is essentially positive. He discusses all those tests which it is desirable to make on lightning protective apparatus so as to assure their satisfactory operation, their operativeness as far as our present knowledge of lightning phenomena goes. Mr. Thomas' paper shows us what tests we should make, tests that are very difficult to make, and in many cases almost impossible except with special facilities.

I believe the conclusion to be drawn from these two papers is that the testing of a lightning-arrester is not the same as the testing of other electrical apparatus. Other apparatus can be tested before the customer and approved, but with the lightning-arrester it is essentially a test of a type to be made on one or a few samples of the arrester, to show whether it—or rather a duplicate of it—will probably be able to cope with the lightning phenomena. After carrying out all of these tests, for instance to determine the limits of the discharge capacity, there will probably be not much left of that particular lightning-arrester. Hence the testing of the lightning-arresters is somewhat similar to that of incandescent lamps. Incandescent lamps cannot be completely tested for life without destruction, and only a certain small percentage of the product is tested, and the rest judged by the performance of the tested (and destroyed) percentage.

The first attempt to test lightning-arresters similar to standard apparatus is given in Mr. Neall's paper. Naturally, such a test is to some extent rather dangerous to the arrester as well as to the system. It is the starting of a discharge of an induction coil. If, instead of a vibrator operating the induction coil, we operate it by a Wehnelt interrupter, or substitute in its place a

Tesla transformer to set off the discharge, it gives a very good way of testing the endurance of the arrester for the recurrent surge as described by Professor Creighton. That means that in all probability in the case of all the commercial arresters at present in use it would be from a few minutes to a few seconds before they would go up in conflagration, because most arresters are built to cope with transitory surge oscillations, transient discharges, and not with recurrent surges. This method of testing by sending a single impulse through by closing the switch of the Ruhmkoff coil, and immediately opening it, will give a single discharge or a few successive discharges, but by closing the switch and keeping it closed, with the rapidly operating induction coil or Tesla transformer, it will give a recurrent surge such as is met with in practice with a spark discharge between the cable conductor and the cable armor, or with the spark discharge from an isolated transmission line to ground through a broken insulator.

Such a recurrent surge as we know now is not taken care of by most types of lightning-arrester, but requires additional protective devices, as explained by Professor Creighton. It requires an aluminum cell permanently connected from line to ground. That brings up the second point to which I desire to call your attention, and that is that all these statements of tests with different forms of lightning-arresters may possibly have to be modified slightly here and there. For instance, to test the discharge voltage, as laid out by Mr Thomas we cannot always apply the Institute test of gradually raising the voltage until the discharge takes place, and then keep it on for a minute In some types of arrester, as exemplified by the water jet—which we are told gives such good results abroad, especially in countries where lightning is not particularly severe—or the aluminum arrester, there is no definite discharge voltage. Their discharge voltage is the normal operating voltage, because they continuously carry a small current and in such case the test would have to be modified. I especially refer to the aluminum arrester, because in this country where lightning is rather severe I do not think that the water jet would be considered as particularly useful. In this case the test may be made by inserting in series with the lightning-arrester the short-circuited secondary of a transformer, and then suddenly opening the secondary circuit, while energizing the primary with impressed electromotive force, that is, suddenly raising the voltage on the lightning-arrester by a certain definite value, say 5%, or 10%, or 50%, and then measuring the instantaneous rush of the discharge current. The discharge current, even if the rise of voltage is moderate, say 10%, may be very large in the first moment, but rapidly dies out, the lightning-arrester adjusting itself to the higher voltage. Some other modifications of tests would also have to be made, which would be obvious to the one who studies the particular lightning-arrester. In general, the conclusion is that the testing of the lightning-arrester, to get absolute results on its probable performance in actual operation, is not so simple as testing other apparatus, generators, etc., but requires the coöperation of the customer with the manufacturer and also requires special facilities, quite elaborate facilities, really to get a complete and reasonable and effective test.

P. H. Thomas: I am surprised that none of the manufacturers of commercial lightning-arresters has made a protest against the rather uncertain and indefinite tests here proposed for Institute sanction, as I am inclined to be sceptical about the wisdom of the Institute's attempting to standardize lightning-arrester tests at the present time. The Institute should be very careful about approving methods of testing lightning-arresters that cannot be conducted by engineers of ordinary experience, methods by which such engineers would not usually be able to produce identical results. There are not more than one or two of the tests proposed that can be so conducted by the average engineer. Mr. Creighton's recommendations seem to be intended for individual research by experts and designers of lightning-arresters, rather than tests to be undertaken by commercial engineers.

I feel also doubtful about the wisdom of making any more definitions at present. It is hard to keep track of definitions made by the international societies and conventions; and if we make any more I think it will lead to complete confusion.

It is too soon to attempt to make standard rules for testing electrolytic arresters. There is a good deal of laboratory information, perhaps, and a good deal of inference as to what their characteristics will turn out to be; but, until a considerable number of engineers become pretty familiar with them, and the plants in which they are installed have seen more experience, I think we should refrain from adopting any standard tests. I do not wish to make any insinuations about the value of the electrolytic arrester, but I think we should go slow on general principles before standardizing tests.

Mr. Neall's paper shows an ingenious arrangement and one which might work conveniently in some cases, provided the induction coil will cause sparking over the gap, which I think is doubtful in most cases. As Dr. Steinmetz has pointed out, it is necessary to have a single spark at a time, not a series of sparks more extended, except in the case of an endurance test. With one or two exceptions, relative tests are the only valuable tests. It is not possible to say that the arrester has so many absolute units of protective power.

W. S. Lee: If some system could be devised for testing the lightning-arresters where installed it would be an excellent thing, and I think it should be given some consideration as it would help out the man who thinks he has an arrester but really has not. We should have some test, if possible, which could be made periodically, to find out whether the arresters on lines are good or useless. Having to contend with a great deal of trouble every year with lightning-arresters, I think the time has come when some reliable tests should be devised which could be applied to the arresters while they are in service.

N. J. Neall: In answer to Professor Creighton's question—the requisite spark strong enough for a given discharge has not been fully determined. For low-voltage preliminary experiments it was easy to obtain more spark than was actually necessary in order to have the arc take the spark as a bridge.

Another important consideration, discovered almost at the outset, is the impossibility of obtaining a spark from gaps to ground if the condenser heads are connected directly to the high-tension feeders, because the power in the high-tension system is sufficient to hold the condenser charged. It is for this reason that connection is made to the middle point of the series of gaps between the line and ground in order that the discharge may have full play in both directions.

I should like to make the following suggestions in connection with the papers by Messrs. Creighton and Thomas.

1. *Nomenclature.* The names, definitions, and recent classification of lightning-arrester characteristics while entirely proper from the standpoint of theory, strike me as being unduly elaborate and unnecessary for the purpose for which standardization rules were originated. It seems to me that nomenclature can be overdone, not to speak of misleading the general manufacturer and operator who is not necessarily a technician.

Practical lightning development and testing should be kept as simple as possible in order to free it from any mystery which can be so easily attached to this branch of the art.

2. *Apparatus.* It will be observed that the methods proposed for the development of lightning protective apparatus, even under the most favorable laboratory conditions, do not permit a thorough investigation of the devices under operation much above 5000 volts.

Practical application of lightning protective apparatus is now fairly well established up to 30,000 volts. What is needed is information as to its behavior at a higher voltage, 50,000 volts and so on, so that in selecting any standard test in its development this difference in the character of the service should be borne fully in mind.

As a matter of fact the only test of final value is a practical one. A method to this end has been described previously in the PROCEEDINGS. It consists in a careful observation by means of tell-tale papers as to the operation of all protective apparatus on a given system so that any recommendations by the Institute under the head of Standardization Rules should give some mention of this.

3. *Tests proposed.* I heartily approve of the tests proposed by Mr. Thomas as being practical. While they do not cover the case absolutely, they furnish all the information that would usually be required.

If to his proposed tests, a further one should be added to cover investigation by means of tell-tale papers over a long period, there should be sufficient data to eliminate considerable uncertainty.

4. *Needle-point spark-gap.* It seems to me that the most serious danger to the general engineering field lies in the proposed " standardization " of the needle-point spark-gap.

Those members of the Institute who have studied spark-gap performance know that it is very difficult to check the curve which has so far been accepted as standard. Now merely to extend the range of readings on this curve at higher voltages without a thorough study of the phenomena entailed strikes me not only as injudicious, but likely to destroy the prestige which should attend the publication of any data of this character.

It is not my intention to go into the characteristics of spark-gaps of various forms for voltage measurements, since this would well be the subject of a number of papers. It is of as much importance as contributions on lightning-arrester tests. I would therefore respectfully protest against the unqualified use of this form of gap, particularly for very high voltages as at present proposed; in its place I would substitute the gap made with spherical noses backed by metallic discs in order to reduce the opening for a given voltage as well as to straighten and fix the curve therefore.

Charles E. Waddell (by letter): The mountain and Piedmont districts of North Carolina are subject to severe electrical storms of frequent occurrence. On the breaking of winter in the latter part of February or the early part of March, the first destructive storms usually occur; then follows a lapse until the latter part of May or early June, at which time they are at their worst, and from which climax there is a gradual diminution in violence until, early in September, the electrical storms practically cease.

As it is the expressed purpose of the Institute to gather all information pertaining to the subject of lightning, thereby hoping to correlate sufficient data to solve the problem of protection, it is purposed in this paper to recite two instances a little out of the ordinary.

The plant that has suffered more than any other in the mountains is that of the Haywood Power Company on the Pigeon river, twelve miles from Waynesville. The equipment consists of a 400-kw. three-phase, 60-cycle, 13,000-volt hydroelectric unit. The 12-mile transmission line is composed of three No. 2 B. & S. aluminum cables, supported on Thomas 5-T insulators, and on wood poles spaced 200 feet apart. The line runs over mountain ranges and across valleys, touching altitudes of 4000 or 5000 feet.

The lightning protection originally installed was of the highest grade of one of the well-known arresters. Some little difficulty was experienced in obtaining a good " ground ", but after this was overcome the management felt perfectly safe. The opening of the following season was, however, heralded by the destruction of coil after coil in the generator, until at the time the author was called in, out of 54 coils in the armature 40 had been burned out and repaired, and the machine was then running with 13 coils out. Matters had reached a point

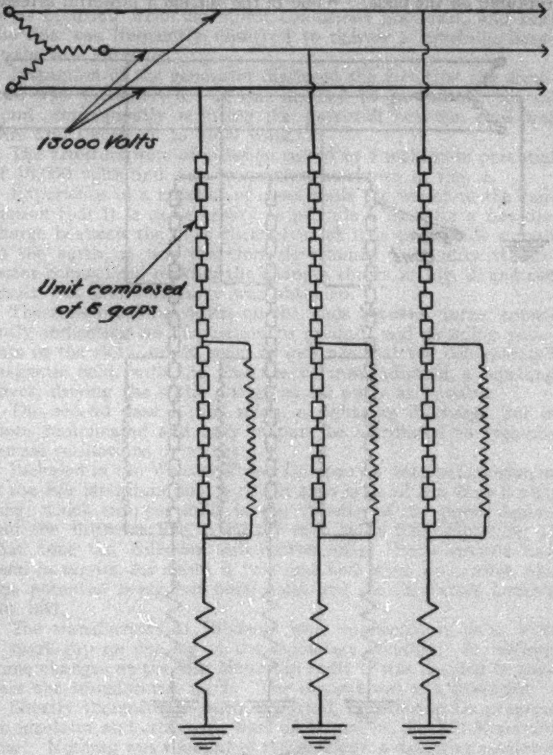

Fig. 1.

where on the slightest manifestation of an electrical disturbance the plant was shut down.

An examination revealed the singular fact that not a single coil had grounded on the frame, but had in every instance ruptured on the ends. While in the station a powerful arrester

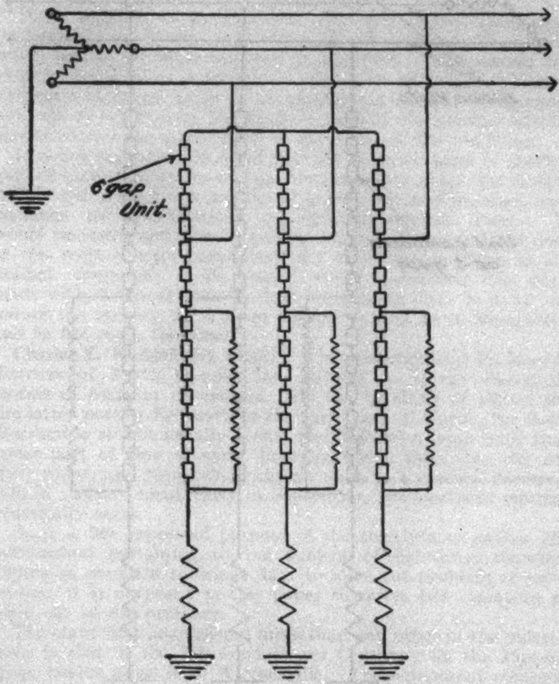

Fig 2

discharge took place, and it was observed that the polyphase electrostatic ground detector which had previously been in a quiescent state became most unstable, erratically fluctuating first one way and then the other, and this was followed in a few moments by the giving way of a coil, and the inevitable shutdown.

The writer concluded that the rupture was due to a static stress that slowly built up, and that the inductive discharge from the electrical storm merely intensified the effect; this opinion was sustained by the attendant's statement, that ruptures occurred when no storm conditions prevailed, and that the line was frequently observed to deliver a brush-discharge at the wire entrance.

Inspection of the generator disclosed the fact that the armature was Y-connected. It was decided to ground the neutral point, consequently reducing the potential between each line wire and the earth to 7500 volts.

The arresters were of a design suited to a maximum potential of 18,000 volts and were connected as shown in Fig. 1.

Experience in a number of cases leads the writer to the conviction that it is as necessary to provide a path for a free discharge between the lines themselves as it is to provide a path to the earth, it was therefore determined to modify the arrester connection, making the changes shown in Fig. 2, and the result was that immunity was obtained.

The coils breaking down on the ends between turns, apparently indicating no disposition to ground, and avoiding puncture in the slots, would seem to indicate that the concentrated magnetic field, with the presence of iron, afforded a repelling effect, driving the static charge as far away as possible.

The second case is not solely a lightning discharge but is more complicated and may in part be attributed to high-potential oscillations or waves.

Included in the Weaver Power Company's distribution system is the Elk Mountain line, a circuit that is in all less than a mile long, which supplies mills in the vicinity of the power house, and the Biltmore line, a circuit nine miles long supplying at that time the Biltmore sub-station only. Both circuits had been in service for about a year and had given no trouble, the line potential being but 6600 volts and the insulators Locke's No. 298.

The transformers at Biltmore were connected in delta with a spark-gap on one leg of the secondary winding. In making some changes at the Elk Mountain mills it was decided to connect the transformers in Y. The neutral was not grounded.

Shortly thereafter a storm occurred, and during its progress an insulator and cross-arm were destroyed on the Elk Mountain line. Nothing was thought of the incident, a defective insulator being assigned as the cause; but the second, third, and fourth repetition of the trouble led to the conclusion that the insulators were not at fault, and that a more subtle cause was responsible.

Not long after the lightning season was over, an underground cable broke down on the Biltmore distribution system, followed, as it always is, by a continuous discharge on the secondary spark-gap. While this was occurring, the main plant telephoned that an arm and insulator were burning on the Elk Mountain line. The discharge at Biltmore was then saddled with the responsibility, and it was decided to provide the neutral of the transformers at the Elk Mountain mills with a spark-gap. This done, it was observed that when one line discharged the other inevitably followed. Since that time no more insulators have given way.

In each of the foregoing instances stress was purposely laid on the type of insulator In the case of the Haywood Power company the insulator was of a pattern that afforded very little leakage. The insulator of the Weaver Power Company affords a considerable leakage. The lines of the North Carolina Power Company parallel those of the Weaver Power Company, and are also equipped with an insulator on which the leakage is negligible.

With the exception of a few potential transformers destroyed when the plant first started, and the above trouble, the Weaver company has been practically safe from lightning troubles, while the other two concerns have experienced not a little inconvenience and loss. In view of these circumstances it would seem not an unreasonable conclusion that a slight leakage distributed over an entire distribution system affords considerable protection against static discharges, and that occasionally by the merest accident a condition of this kind is obtained.

Where violent discharges have passed over the arresters in the Weaver Power Company's station in every case that was investigated it was found that such discharges had occurred immediately before rain started to fall, and that once the insulators, arms, and poles were wet the discharges became less frequent and less severe, a fact that in the author's opinion tends to confirm the above theory.

In justice to the manufacturers of the insulators, it should be stated that the existence of leakage on the particular type is no reflection on the quality, for they are in every respect eminently satisfactory, but is due to the use of a type scarcely large enough for the service.

*A paper presented at the Annual Convention
Meeting of the American Institute of Electrical Engineers, Niagara Falls, June 25, 1907.*

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INDUCTIVE DISTURBANCES IN TELEPHONE LINES.

BY LOUIS COHEN.

The inductive action of one telephone line on another, producing what is commonly known as cross-talk, presents an important problem to the telephone engineer. The induction is both electromagnetic and electrostatic. A variable current passing through any circuit is accompanied by a variable magnetic field, which will produce electric currents in neighboring circuits. In addition to this there exists also an electrostatic effect, a charge on one conductor will induce charges on all neighboring conductors, and any variation in the charge will produce an electric current. We thus have two distinct phenomena acting simultaneously, both causing trouble on telephone lines. It is to be noticed, however, that the two effects act in opposite directions. The establishment of a current in one circuit is accompanied by an induced current in any neighboring circuit in the opposite direction, while when the current in the inducing circuit is decreasing, the induced current will be in the same direction. In the case of electrostatic induction the conditions are reversed. When both forms of induction act together we obtain a resultant effect which depends on the various electrical constants of the lines and their relative importance. It would appear therefore quite evident that to obtain a knowledge of the effect due to induction, we must first be able to ascertain the relative importance of one form of induction as compared with the other, and to determine the factors which enter in fixing the magnitude of each. A thorough knowledge of these factors may be of considerable assistance in improving the conditions of telephone lines, or at least it may suggest some methods for overcoming induction effects which are a source of considerable annoyance to users of telephones.

In a paper presented before the American Institute of Electrical Engineers in 1891,* Mr. J. J. Carty discussed a series of experiments which he had conducted to determine the relative importance of the electrostatic as compared with the electromagnetic induction. His conclusions were that the electromagnetic effect is entirely negligible as compared with the electrostatic effect; in fact in his experiments he has not been able to detect any electromagnetic effect at all. In the discussion of his paper Mr. Carty made the following statement:

> "I go so far as to set forth that the effect of electromagnetic induction between parallel telephone wires may be neglected. That is, that when a man is talking on one wire and his speech is heard by induction on a parallel wire, that that speech finds its way between the two wires by virtue of electrostatic induction, and that electromagnetic induction is entirely negligible."

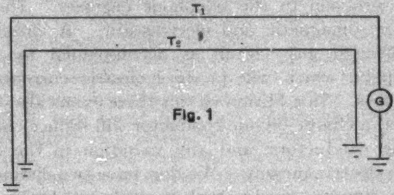

Fig. 1

This view expressed by Mr. Carty has generally been accepted by telephone engineers, and is usually given a very prominent place in all text books on telephony.

In what follows I shall discuss this question from a mathematical standpoint, and shall show that not only is the electromagnetic induction not a negligible quantity, but that in some cases the electromagnetic effect may be much larger than the electrostatic effect; and I shall further show that the results Mr. Carty obtained were correct, that under the conditions of Mr. Carty's experiments he could have obtained only an electrostatic effect. To infer, however, from his results, as Mr. Carty has done, that what is true for the case he experimented with—

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* J. J. Carty, TRANSACTIONS of the A. I. E. E. 1891. Vol. 8, page 114.

a line three hundred feet long—is equally true for a line so many miles long is, as I will show, quite erroneous.

Suppose we have two lines T_1 and T_2 running parallel to each other and both are grounded at the two ends; T_1 may be a power circuit or telephone circuit, G is a source of an alternating electromotive force, and T_2 a telephone line. We wish to consider what is the nature of the induced currents in line T_2.

Let L_1, R_1, C_1, denote the self-inductance, resistance, and capacity per unit length of line T_1, and similar letters with suffix 2 denote the same constants of line T_2; M will denote the mutual electromagnetic inductance and C_{12} the mutual electrostatic inductance. Let also x and y denote the currents, V_1 and V_2 the potentials at any point on the lines T_1 and T_2.

The algebraic sum of the forces acting at any point on the two lines will be given by the following equations:

$$L_1 \frac{dx}{dt} + R_1 x + M \frac{dy}{dt} + \frac{dV_1}{ds} = 0$$

$$L_2 \frac{dy}{dt} + R\ v + M \frac{dx}{dt} + \frac{dV_2}{ds} = 0 \qquad (1)$$

We also have the electrostatic relation,

$$C_1 V_1 + C_{12} V_2 = q_1$$

$$C_2 V_2 + C_{12} V_1 = q_2 \qquad (2)$$

By the aid of the equations of contin

$$\frac{dq_1}{dt} = -\frac{dx}{ds}$$

$$\frac{dq_2}{dt} = -\frac{dy}{ds}$$

we may write equations (2) after differentiating with respect to t in the following form:

$$C_1 \frac{dV_1}{dt} + C_{12} \frac{dV_2}{dt} = -\frac{dx}{ds}$$

$$C_2 \frac{dV_2}{dt} + C_{12} \frac{dV_1}{dt} = -\frac{dy}{ds} \qquad (3)$$

Differentiating equations (1) with respect to *s* we get:

$$L_1 \frac{d^2 x}{d t d s} + R_1 \frac{d x}{d s} + M \frac{d^2 y}{d t d s} + \frac{d^2 V_1}{d s^2} = 0$$

$$L_2 \frac{d^2 y}{d t d s} + R_2 \frac{d y}{d s} + M \frac{d^2 x}{d t d s} + \frac{d^2 V_2}{d s^2} = 0 \qquad (4)$$

If we differentiate equations (3) with respect to *t*, and introduce the values of $\frac{d^2 x}{d s d t}, \frac{d^2 y}{d s d t}$ thus obtained into equations (4) and also the values of $\frac{d x}{d s}$ and $\frac{d y}{d s}$ from equations (3) we shall obtain the following equations:

$$L_1 C_1 \frac{d^2 V_1}{d t^2} + L_1 C_{12} \frac{d^2 V_2}{d t^2} + R_1 C_1 \frac{d V_1}{d t} + R_1 C_{12} \frac{d V_2}{d t}$$
$$+ M C_2 \frac{d^2 V_2}{d t^2} + M C_{12} \frac{d^2 V_1}{d t^2} = \frac{d^2 V_1}{d s^2}$$

$$(5)$$

$$L_2 C_2 \frac{d^2 V_2}{d t^2} + L_2 C_{12} \frac{d^2 V_1}{d t^2} + R_2 C_2 \frac{d V_2}{d t} + R_2 C_{12} \frac{d V_1}{d t}$$
$$+ M C_1 \frac{d^2 V_1}{d t} + M C_{12} \frac{d^2 V_2}{d t^2} = \frac{d^2 V_2}{d s^2}$$

Assuming that the impressed electromotive force be simple harmonic, that is the real part of $E e^{ipt}$ say, then the potentials at any point along the lines will be simple harmonic, and therefore we may put:

$$\frac{d^2 V_1}{d t^2} = - p^2 V_1, \quad \frac{d V_1}{d t} = i p V_1$$

$$\frac{d^2 V_2}{d t^2} = - p^2 V_2, \quad \frac{d V_2}{d t} = i p V_2$$

Introducing these values in equation (5) and rearranging we get:

$$\frac{d^2 V_1}{d s^2} = a_1 V_1 + b_1 V_2$$

$$\frac{d^2 V_2}{d s^2} = a_2 V_2 + b_2 V_1 \tag{6}$$

Where,

$$\begin{aligned} a_1 &= -p^2 L_1 C_1 + i p R_1 C_1 - M C_{12} p^2 \\ b_1 &= -p^2 L_1 C_{12} + i p R_1 C_{12} - M C_1 p^2 \\ a_2 &= -p^2 L_2 C_2 + i p R_2 C_2 - M C_{12} p^2 \\ b_2 &= -p^2 L_2 C_{12} + i p R_2 C_{12} - M C_1 p^2 \end{aligned} \tag{7}$$

Each of the equations (6) contains two dependent variables which make it rather difficult to solve. We can, however, transform equations (6) into equations containing only one dependent variable by the following device:*

Put

$$V_1 = W_1 + W_2$$
$$V_2 = f_1 W_1 + f_2 W_2$$

where f_1 and f_2 are arbitrary constants.

Equations (6) will transform into the following:

$$\frac{d^2 W_1}{d s^2} + \frac{d^2 W_2}{d s^2} = (a_1 + b_1 f_1) W_1 + (a_1 + b_1 f_2) W_2$$

$$f_1 \frac{d^2 W_1}{d s^2} + f_2 \frac{d^2 W_2}{d s^2} = (a_2 f_1 + b_1) W_1 + (a_2 f_2 + b_2) W_2$$

Eliminating first W_1 and then W_2 we get the following equations:

$$(a_2 f_2 + b_2 - a_1 f_1 - b_1 f_1 f_2) \frac{d^2 W_1}{d s^2} + (a_2 f_2 + b_2 - a_1 f_2 - b_1 f_2^2) \frac{d^2 W_2}{d s^2}$$
$$= (a_1 a_2 - b_1 b_2)(f_2 - f_1) W_1$$

$$(a_2 f_1 + b_2 - a_1 f_1 - {}_1b f_1^2) \frac{d^2 W_1}{d s^2} + (a_2 f_1 + b_1 - a_1 f_2 - b_1 f_1 f_2) \frac{d^2 W_2}{d s^2} \tag{8}$$
$$= (a_1 a_2 - b_1 b_2)(f_1 - f_2) W_2$$

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*See O. Heaviside coll. papers, vol. 1, p. 126.

now determine f_2 and f_1 from the equations

$$a_2 f_2 + b_2 - a_1 f_2 - b_1 f_2^2 = 0$$

$$a_2 f_1 + b_2 - a_1 f_1 - b_1 f_1^2 = 0$$

that is,

$$\left.\begin{aligned} f_2 &= \frac{a_2 - a_1 - \sqrt{(a_1 - a_2)^2 + 4\, b_1\, b_2}}{2\, b_1} \\ f_1 &= \frac{a_2 - a_1 - \sqrt{(a_1 - a_2)^2 + 4\, b_1\, b_2}}{2\, b_1} \end{aligned}\right\} \tag{9}$$

Equations (8) will reduce to the following:

$$\left.\begin{aligned} \frac{d^2 W_1}{d\, s^2} &= \overline{K^2}\, W_1 \\ \frac{d^2 W_2}{d\, s^2} &= P^2\, W_2 \end{aligned}\right\} \tag{10}$$

where,

$$\left.\begin{aligned} \overline{K^2} &= \frac{(a_1\, a_2 - b_1\, b_2)\,(f_2 - f_1)}{a_2 f_2 + b_2 - a_1 f_1 - b_1 f_1 f_2} \\ P^2 &= \frac{(a_1\, a_2 - b_1\, b_2)\,(f_1 - f_2)}{a_2 f_1 + b_2 - a_1 f_2 - b_1 f_1 f_2} \end{aligned}\right\} \tag{11}$$

The complete solutions of (10) will be the following:

$$\left.\begin{aligned} W_1 &= A \cos \mu\,(l - s) + B \sin \mu\,(l - s) \\ W_2 &= D \cos \mu_1\,(l - s) + F \sin \mu_1\,(l - s) \end{aligned}\right\} \tag{12}$$

The constants are to be determined from the following boundary conditions:

When

$$s = 0, \qquad V_1 = E\, e^{ipt} \qquad V_2 = 0$$

$$s = l, \qquad V_1 = 0, \qquad V_2 = 0$$

Now,

$$W_1 = \frac{f_1 V_1 - V_2}{f_1 - f_2}, \qquad W_2 = \frac{f_2 V_1 - V_2}{f_2 - f_1}$$

Hence, when $s = 0$

$$W_1 = A \cos \mu l + B \sin \mu l = \frac{f_1 \, E e^{ipt}}{f_1 - f_2}$$

$$W_2 = D \cos \mu_1 l + F \sin \mu_1 l = \frac{f_2 \, E e^{ipt}}{f_2 - f_1}$$

When $s = l$,

$$W_1 = A = 0$$
$$W_2 = D = 0$$

and therefore,

$$B = \frac{f_1 \, E e^{ipt}}{(f_1 - f_2) \sin \mu l}$$

$$F = \frac{f_2 \, E e^{ipt}}{(f_2 - f_1) \sin \mu_1 l}$$

Introducing the values of the constants thus obtained into equation (12) we shall obtain the following values for V_1 and V_2:

$$V_1 = W_1 + W_2 = \left(\frac{f_1 \sin \mu (l - s)}{\sin \mu l} - f_2 \frac{\sin \mu_1 (l - s)}{\sin \mu_1 l} \right) \frac{E e^{ipt}}{f_1 - f_2}$$

$$\tag{13}$$

$$V_2 = f_1 W_1 + f_2 W_2 = \left(\frac{f_1^2 \sin \mu (l - s)}{\sin \mu l} - f_2^2 \frac{\sin \mu_1 (l - s)}{\sin \mu_1 l} \right) \frac{E e^{ipt}}{f_1 - f_2}$$

The values of μ and μ_1 may be obtained by inspection of equation (10) which gives

$$- \mu^2 = \overline{K^2} = \frac{(a_1 a_2 - b_1 b_2)(f_2 - f_1)}{a_2 f_2 + b_2 - a_1 f_1 - b_1 f_1 f_2}$$

$$\tag{14}$$

$$- \mu_1^2 = P^2 = \frac{(a_1 a_2 - b_1 b_2)(f_1 - f_2)}{a_2 f_1 + b_1 - a_1 f_2 - b_1 f_1 f_2}$$

The value of the currents in the two lines can be easily obtained from equation (13) by the aid of equation (3). Thus:

$$-x = \left[C_1 i p \left(\frac{f_1 \cos \mu (l-s)}{\mu \sin \mu l} - f_2 \frac{f_2 \cos \mu_1 (l-s)}{\mu_1 \sin \mu_1 l}\right)\right.$$

$$\left. + i C_{12} p \left(\frac{f_1^2 \cos \mu (l-s)}{\mu \sin \mu l} - \frac{f^2_2 \cos \mu_1 (l-s)}{\mu_1 \sin \mu_1 l}\right)\right] \frac{E e^{ipt}}{f_1 - f_2}$$

$$(15)$$

$$-y = \left[C_2 i p \left(\frac{f_1^2 \cos \mu (l-s)}{\mu \sin \mu l} - \frac{f_2^2 \cos \mu_1 (l-s)}{\mu_1 \sin \mu_1 l}\right)\right.$$

$$\left. + i C_{12} p \left(\frac{f_1 \cos \mu (l-s)}{\mu \sin \mu l} - \frac{f_2 \cos \mu_1 (l-s)}{\mu_1 \sin \mu_1 l}\right)\right] \frac{E e^{ipt}}{f_1 - f_2}$$

Rearranging we obtain:

$$-x = \left((C_1 f_1 + C_{12} f_1^2) \frac{\cos \mu (l-s)}{\mu \sin \mu l}\right.$$

$$\left. - (C_1 f_2 + C_{12} f_2^2) \frac{\cos \mu_1 (l-s)}{\mu_1 \sin \mu_1 l}\right) \frac{i p E e^{ipt}}{f_1 - f_2}$$

$$(16)$$

$$-y = \left((C_2 f_1^2 + C_{12} f_1) \frac{\cos \mu (l-s)}{\mu \sin \mu l}\right.$$

$$\left. - (C_2 f_2^2 + C_{12} f_2) \frac{\cos \mu_1 (l-s)}{\mu_1 \sin \mu_1 l}\right) \frac{i p E e^{ipt}}{f_1 - f_2}$$

The second equation of (16) gives us the final expression for the currents in any wire due to electromagnetic and electrostatic induction of a parallel wire. The inducing line may be part of a power circuit, lighting circuit, or a similar telephone line. In deducing equations (16) we have taken account of the difference in dimensions, or electrical constants, of the two lines which react upon each other, which will of course be the case if we wish to calculate the currents induced in a telephone line by a power circuit running parallel to it.

According to some recent reports, the introduction of the single-phase electric railway plays havoc with service on telephone and telegraph lines which parallel the railways. This will in all probability be a very serious problem, and a careful consideration of equation (16) will give us a better insight into the nature of the problem and the magnitude of the disturbance. It may also possibly suggest some means for eliminating these disturbances or at least reducing them to a minimum. I hope to consider this phase of the problem in another paper, but for the present I shall limit my discussion to the case of two parallel telephone lines.

If it is the influence of two telephone lines on each other that we wish to investigate, then equations (16) will be somewhat simplified; for in that case we find by examining equations (6) that

$$a_1 = a_2 \qquad\qquad b_1 = b_2$$

equations (9) will therefore reduce to

$$f_1 = -f_2 = 1$$

Hence equations (16) will become,

$$x = \tfrac{1}{2}\left((C+C_{12})\,\frac{\cos\mu\,(l-s)}{\mu\sin\mu\,l} + (C-C_{12})\frac{\cos\mu_1\,(l-s)}{\mu_1\sin\mu_1\,l}\right) i\,p\,E\,e^{ipt}$$

$$-y = \tfrac{1}{2}\left((C+C_{12})\,\frac{\cos\mu\,(l-s)}{\mu\sin\mu\,l} - (C-C_{12})\frac{\cos\mu_1\,(l-s)}{\mu_1\sin\mu_1\,l}\right) i\,p\,E\,e^{ipt} \tag{17}$$

The values of μ and μ_1 are given by equations (14) which in the case of two parallel wires reduce to the following:

$$\begin{aligned} -\mu^2 &= a+b = -p^2\,(L+M)\,(C+C_{12})+i\,p\,R\,(C+C_{12}) \\ -\mu_1^2 &= a-b = -p^2\,(L-M)\,(C-C_{12})+i\,p\,R\,(C-C_{12}) \end{aligned} \tag{17}$$

μ and μ_1 are of course complex quantities, putting

$$\mu = \alpha+i\,\beta \qquad \mu_1 = \alpha_1+i\,\beta_1$$

and solving for α, β, α_1 and β_1 we get

$$\begin{aligned} \alpha &= \sqrt{\tfrac{1}{2}\,p\,(C+C_{12})\ \left[\sqrt{p^2\,(L+M)^2+R^2}+p\,(L+M)\right]} \\ \beta &= \sqrt{\tfrac{1}{2}\,p\,(C+C_{12})\ \left[\sqrt{p^2\,(L+M)^2+R^2}-p\,(L+M)\right]} \\ \alpha_1 &= \sqrt{\tfrac{1}{2}\,p\,(C-C_{12})\ \left[\sqrt{p^2\,(L-M)^2+R^2}+p\,(L-M)\right]} \\ \beta &= \sqrt{\tfrac{1}{2}\,p\,(C-C_{12})\ \left[\sqrt{p^2\,(L-M)^2+R^2}-p\,(L-M)\right]} \end{aligned} \tag{18}$$

It remains now to separate the values of x and y into the real and imaginary parts, for the actual currents in the lines will be the real parts of the values of x and y as given by equation (17). Now

$$\frac{i\,p\,E\,e^{ipt}}{\mu \sin \mu\, l} = \frac{i\,p\,E\,(\cos p\,t + i \sin p\,t)}{(\alpha + i\,\beta) \sin\,(\alpha + i\,\beta)\,l} =$$

$$\frac{2\,(\alpha - i\,\beta)\,(\sin \alpha\,l\,(e^{\beta l} + e^{-\beta l}) - i \cos \alpha\,l\,(e^{\beta l} - e^{-\beta l}))\,E\,i\,p\,(\cos p\,t + i \sin p\,t)}{(\alpha^2 + \beta^2)\,[\sin^3 \alpha\,l\,(e^{2\beta l} + 2 + e^{-2\beta l}) + \cos^2 \alpha\,l\,(e^{2\beta l} - 2 + e^{-2\beta l}]}$$

the real part of which is

$$\frac{2\,E\,p\Big[\Big\{\beta \cos \alpha\,l\,(e^{\beta l} - e^{-\beta l}) - \alpha \sin \alpha\,l\,(e^{\beta l} + e^{-\beta l})\Big\} \sin p\,t + \Big\{\beta \sin \alpha\,l\,(e^{\beta l} + e^{-\beta l}) + \alpha \cos \alpha\,l\,(e^{\beta l} - e^{-\beta l})\Big\} \cos p\,t\Big]}{(\alpha^2 + \beta^2)\,(e^{2\beta l} + e^{-2\beta l} - 2 \cos 2\,\alpha\,l)}$$

$$= \frac{2\,E\,p \sin\,(p^{t}\,\phi)}{\sqrt{(\alpha^2 + \beta^2)\,(2 \cos h\,2\,\beta\,l - 2 \cos 2\,\alpha\,l)}} \tag{19}$$

Where $\tan \phi =$

$$\frac{\beta \sin \alpha\,l\,(e^{\beta l} + e^{-\beta l}) + \alpha \cos \alpha\,l\,(e^{\beta l} - e^{-\beta l})}{\beta \cos \alpha\,l\,(e^{\beta l} - e^{-\beta l}) - \alpha \sin \alpha\,l\,(e^{\beta l} + e^{-\beta l})} \tag{20}$$

When $\beta\,l$ is a very small quantity, then approximately

$$\tan \phi = -\frac{\beta}{\alpha} \tag{21}$$

When $\beta\,l$ is very large, then the above equation will be approximately

$$\tan \phi = \frac{\beta \sin \alpha\,l + \alpha \cos \alpha\,l}{\beta \cos \alpha\,l - \alpha \sin \alpha\,l} \tag{22}$$

At the end of the line, say when $s = l$, the values of the currents will therefore be given by the following equations:

$$\begin{aligned} -x_l &= E\,p\left\{\frac{(C_1 + C_{12}) \sin\,(p\,t + \phi)}{\sqrt{(\alpha^2 + \beta^2)\,(2 \cos h\,2\,\beta\,l - 2 \cos 2\,\alpha\,l)}} + \frac{(C_1 - C_{12}) \sin\,(p\,t + \phi_1)}{\sqrt{(\alpha_1^2 + \beta_1^2)\,(2 \cos h\,2\,\beta_1\,l - 2 \cos 2\,\alpha_1\,l)}}\right\} \\ -y_l &= E\,p\left\{\frac{(C_1 + C_{12}) \sin\,(p\,t + \phi)}{\sqrt{(\alpha^2 + \beta^2)\,(2 \cos h\,2\,\beta\,l - 2 \cos 2\,\alpha\,l)}} - \frac{(C_1 - C_{12}) \sin\,(p\,t + \phi_1)}{\sqrt{(\alpha_1^2 + \beta_1^2)\,(2 \cos h\,2\,\beta_1\,l - 2 \cos 2\,\alpha_1\,l)}}\right\} \end{aligned} \tag{23}$$

The second equation of (23) represents the current at one end of the line T_2 due to the electromagnetic and electrostatic induction. We may put equation (23) in a more convenient form, thus:

$$y_l = E\,p\sqrt{A^2+B^2-2\,A\,B\cos(\phi-{}_1\phi)}\,\sin(p\,t+\phi) \qquad (24)$$

Where

$$A = \frac{C-C_{12}}{\sqrt{(\alpha_1^2+\beta_1^2)\,(2\cos h\,2\,\beta_1\,l-2\cos 2\,\alpha_1\,l)}}$$

$$B = \frac{C+C_{12}}{\sqrt{(\alpha^2+\beta^2)\,(2\cos h\,2\,\beta\,l-2\cos 2\,\alpha\,l)}} \qquad (25)$$

$$\tan\phi = \frac{A\cos\phi_1-B\cos\phi}{A\sin\phi_1-B\sin\phi}$$

The maximum value of the current will evidently be,

$$E\,p\sqrt{A^2+B^2-2\,A\,B\cos(\phi-\phi_1)}.$$

Now to find the ratio of the electrostatic to the electromagnetic induction, we calculate the value of y_l as given by equation (24) first on the supposition that $M=0$; that is, that the whole effect is purely electrostatic, and then calculate the value of y_l on putting $C_{12}=0$; that is, assuming that the effect is purely electromagnetic. We can thus obtain an estimate of the relative importance of the two forms of induction in causing disturbances in parallel lines. The values of the various electrical coefficients which enter into the calculations were determined from formulas given by Mr. Heaviside* in his collected papers, which are as follows:

$$L = \tfrac{1}{2}+2\log\frac{2\,h}{r}$$

$$M = \log\frac{d^2+(h_1+h_2)^2}{d^2+(h_1-h_2)^2}$$

$$C_1 = \frac{2\log\dfrac{2\,h}{r}}{\left(2\log\dfrac{2\,h}{r}\right)^2-\left(\log\dfrac{d^2+4\,h^2}{d^2}\right)^2} \qquad (26)$$

$$-\,C_{12} = \frac{\log\dfrac{d^2+4\,h^2}{d^2}}{\left(2\log\dfrac{2\,h}{r}\right)^2-\left(\log\dfrac{d^2+4\,h^2}{d^2}\right)^2}$$

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*O. Heaviside collected papers, Vol. 1, pp. 44 and 101.

These formulas apply to the case of parallel suspended wires where h is the height above the ground, d is the distance between the wires, and r is the radius of the wire.

Let us now consider an example; suppose the two wires are 1.25 cm. apart, and at about 1000 cm. above the ground let the radius of each wire be 0.1 cm., then we find

$L = 0.00203$ henry per kilometre.
$M = 0.00147$ " " "
$C = 0.0118$ mf. " "
$-C_{12} = 0.0088$ mf. " "
$R = 3$ ohms per kilometre approximately.

Using these values for the constants of the lines, I have calculated the maximum of the current y_l, as given by equation (24),

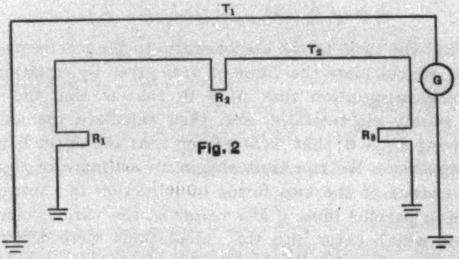

Fig. 2

first assuming that we have only electrostatic induction; that is, $M = 0$, and second assuming that we have only electromagnetic induction; that is, $C_{12} = 0$. The ratios of the two forms of induction for various lengths of lines given below:

	$\frac{e.\ s.}{e.\ m.}$
0.1 km.	0.02
100 km.	0.44
1000 km.	1.6

From this short table it will be seen that for the particular case under consideration, the electromagnetic induction is far larger than the electrostatic; but as the length increases the electrostatic is gaining more rapidly than the electromagnetic, and thus at 1000 km., the electrostatic has overpowered the electromagnetic. In obtaining the above results we have assumed that our line does not have any telephone receiver in it, which is of course not the important case. In the case of a long line, however, say 100 km. or more, where the inductance of the line is large, compared with the inductance of the receiver, the introduction of a receiver will not modify the result to any great extent, but in the case of a short line, the introduction of one or more receivers may affect the results to a very great extent. Let us consider for example one of Mr. Carty's experiments.

There are two lines of about 0.1 km. long stretched side by side at a distance of about 1 cm. and there are three telephone receivers in the second line, the complete solution of this problem is not of course so simple, yet as an approximation we may consider the introduction of the telephone receivers in such a short line as a distributed inductance and resistance. If the inductance of each receiver is 0.05 henry and its resistance is 50 ohms, then for such a short line, the inductance per unit length will be $L = 1.5$ henry and $R = 1500$ ohms. Assuming these to be the constants of our line we find, on calculating as in the previous cases, that the current due to electromagnetic induction is practically zero, and it is only the current due to electrostatic induction that has any appreciable value, and this is what Mr. Carty obtained experimentally. To infer from this that electromagnetic induction is negligible in all cases is however, certainly incorrect. In the case of a long line, say 500 km., the induction and resistance of the telephone receivers will not modify to any great extent the constants of the line, and in that case the electromagnetic induction is just as important as the electrostatic induction. Which is the more important depends a great deal on the length of the lines, their height above the ground, and their distance apart. By varying any one of the above factors we shall vary the ratio of the electromagnetic to the electrostatic induction.

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A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N.Y., June 26, 1907.

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CHOKE-COILS VERSUS EXTRA INSULATION ON THE END-WINDINGS OF TRANSFORMERS

BY S. M. KINTNER

Surges along a transmission line are stopped and thrown back by choke-coils in a manner analogous to the reflection of water waves by a breakwater at the entrance to a harbor. The quiet of a harbor is obtained by setting up a strong wall capable of withstanding the shock of the waves that strike against it; so is the analogous quiet of a transformer obtained by placing a choke-coil in the path of a disturbance.

A choke-coil will be effective in reflecting and shielding all back of it according to its strength. The strength of a choke-coil is measured by its inductance and its insulation. If the former is small, but little reflection will take place, the surge passing through the coil and continuing beyond it. If the insulation of the coil is weak and the inductance is of sufficient value to retard the on-coming wave and throw it back on to the line, the rise of voltage will cause a discharge over the coil-face and the wave will continue past the coil. These two conditions can be likened to a breakwater consisting of piling spaced so as to have little effect in retarding an incoming wave in the first instance; and in the second instance to a breakwater of insufficient height, so that the waves pass over it.

With a given choke-coil on a given line, a certain fixed amount of protection will be afforded any apparatus placed back of the coil. There is no relation between the coil and the apparatus being protected that will make the coil more or less effective in its operation of throwing back surges that come in from the line. The choke-coil will produce the same percentage of reflection regardless of what it is protecting, and consequently can be said to be affording the same protection.

Tests indicate that the same percentage of protection will be afforded by the same coil for all parts of the same transformer; that is, measurements made over 200 turns of the winding of a transformer which was being subjected to static surges from a discharging condenser: first, when the transformer was unprotected; secondly, when it was protected by a choke-coil, showed practically the same percentage of protection afforded by the choke-coil when the measurements were repeated over only 20 turns of the transformer. A long series of tests, the results of a part of which have been recently made known to the Institute by Mr. R. P. Jackson,* have convinced the writer of the truth of the above statements.

In choosing a choke-coil for a particular installation, the matter resolves itself into a consideration of: 1, the possible surge the apparatus can withstand safely; 2, the probable surge that can be transmitted over the proposed line, the line insulation indicating the maximum voltage that the surge can have during transmission; 3, the maximum allowable inductance that will not seriously affect the line regulation if an external choke-coil is used; 4, a consideration of the amount of money to be expended for choke-coils as insurance against interruption; 5, the selection of a choke-coil which will most nearly meet the above conditions, the selection being guided by the above, combined with the results of tests and curves similar to those shown in Mr. Jackson's paper.

The question of whether part of the transformer winding should be made strong enough to withstand the surges—and thus have within its own windings a choke-coil that protects the rest of the apparatus—or whether an extra coil should be used, will be discussed below.

The following is a list of the advantages and disadvantages of separate choke-coils.

Advantages:

1. On a choke-coil there is normally no voltage between turns, and consequently no tendency to hold a short-circuit in the event of a momentary surface-discharge.

2. The choke-coil permits the construction of a transformer with uniform insulation throughout. This permits the safe

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* PROCEEDINGS A. I. E. E. December, 1906, p. 843.

working of such a transformer with several methods of connection to the line.

3. The choke-coil allows the safe use of a cheaper transformer.

4. The choke-coil can be insulated much more strongly than a transformer.

Disadvantages:

5. Increase in the number of pieces of apparatus.

6. Increase in complication of station wiring when external choke-coils are used.

1. One of the greatest advantages of choke-coils over extra insulation on the transformer windings lies in the fact that the choke-coil does not normally have a voltage between turns. In the event of a choke-coil insulation failing between turns, nothing in the nature of a short-circuit results, as there is no voltage-difference to maintain an arc. On the other hand, a failure between turns in the insulation of a transformer is vital, and it is almost certain to result in a transformer burn-out. A part of the choke-coil will be cut out and will be inoperative, and consequently the coil less effective as a whole is the worst that can result from such a failure in the coil insulation.

2. The second point of superiority of the choke-coil—allowing the use of a transformer which is uniformly insulated—is of great advantage to the builder, as well as to the operator.

In the majority of specifications for power transmission transformers, it is required that the transformer be capable of operating at one-half voltage at full rated capacity. In general, it is expected also that occasion may arise when the transformer may be operated either in star or delta connection.

It is evident that to meet all the above conditions with certain parts of the transformer specially insulated, involves some very complicated insulation arrangements, and requires extra insulation on a large part of the whole transformer.

3. In consideration of the third point, that of cost of transformer, it should be remembered that the better grade of power transmission transformers of 1000 kw. and upward are wound with copper ribbon, one turn per layer. These coils are insulated uniformly throughout, so as to stand momentary voltages of from 5000 to 9000, between turns. In order to get this result, only about 8 to 10% of the available winding space can be used for copper, the rest being given up to solid insulation and oil-ventilating ducts. An increase in insulation over the above is not desirable with the insulating materials in use at this time;

for two reasons: first, the coils cannot be made strong enough mechanically to stay in place under the shocks to which they are subjected; secondly, the extra insulation retains the heat from the copper, and thus either burns out or necessitates a much lower rating of the transformer.

It is very difficult for workmen to handle large coils with extra heavy insulation without injury to the insulation.

It is therefore evident that a cheaper transformer can be employed when a protecting choke-coil is used.

4. The fourth advantage of the choke-coil is that much better insulation can be obtained in it than in a transformer. This is due to the fact that more material can be used between turns, and it can be disposed to better advantage by allowing more extension beyond the copper than can be employed economically in a transformer coil; also, the shape of the coil is much simpler than that of the average transformer coil and thus more readily lends itself to better insulation.

5-6. The disadvantages of the choke-coil over the extra insulation are two in number; first, an increase in the number of pieces of apparatus; secondly, an increased complication in the station wiring when an external choke-coil is used. Both of these disadvantages are very materially reduced when it is permissible to mount the choke-coils inside of the transformer tank. It is thus possible to make the choke-coil a part of the transformer terminal, the coil being connected on the inner end of the terminal.

For some installations it is possible to use choke-coils mounted out in the air and thus made a part of the station wiring, but in general the oil-insulated coil is to be preferred. Past practice has been to have each oil-insulated choke-coil mounted in its own tank, but there seems to be no good reason why they cannot be placed inside the transformer tank and thus save considerable floor space as well as outside wiring.

After a thorough consideration of what is involved in the above points, it is the writer's opinion that, for a given expenditure to provide protection against surges, more can be obtained by the use of choke-coils than by extra insulation on the transformer.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, June 26, 1907.

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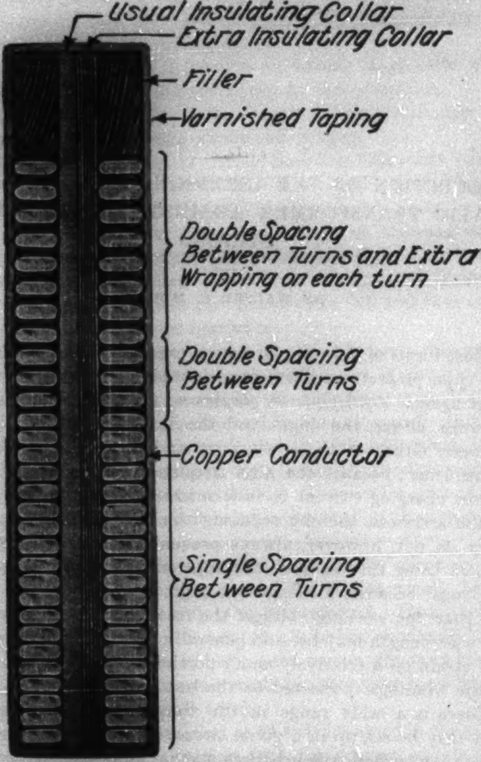
PROTECTION OF THE INTERNAL INSULATION OF A STATIC TRANSFORMER AGAINST HIGH-FREQUENCY STRAINS

BY WALTER S. MOODY

Most forms of lightning-arresters, especially those of the multigap type, protect transformers against high-frequency even better than against low-frequency strains so far as these strains exist between either the high- and the low-potential windings, or between either of these windings and any other part of the transformer; because the high frequency causes a greater condenser charging current to flow across the gaps at the line end of the arresters, thereby reducing the resistance of these gaps. They do not, however, always prevent strains far in excess of normal being thrown upon the adjacent turns and layers of the windings; because, although the high frequency strain may be less than the working voltage, the frequency, and consequently the wave-length may be, and generally is, such as to concentrate this strain on a relatively small portion of the turns at the end of the windings connected to the line.

There is a wide range in the frequency of the oscillations that may be set up in a given circuit under varying conditions due to atmospheric disturbances, partial grounds, switching, etc., this range easily extending from normal to several hundred thousand cycles. In the effort to impede all or a greater part of the high-frequency disturbances that try to penetrate the transformer windings, it has been quite common practice to place reactance-coils between the lightning-arresters and the transformers. While such coils are undoubtedly advisable and are quite effective, their use is attended with some objections.

A wide range is found in the size of such coils employed by different authorities, varying from, say, 10 ft. of conductor


Usual Insulating Collar
Extra Insulating Collar
Filler
Varnished Taping
Double Spacing Between Turns and Extra Wrapping on each turn
Double Spacing Between Turns
Copper Conductor
Single Spacing Between Turns

Cross Section of Transformer Coil Showing Reinforced Insulation

FIG. 1

wound in a small diameter open spiral to several hundred feet wound in forms more difficult to insulate. Evidence of more or less effectiveness of any of the different forms is usually forthcoming, inasmuch as sooner or later there are sure to be conditions that will generate very high voltages and frequencies.

If, however, the reactance is such as to be effective against moderately high-frequency oscillations, it must, since it is connected between lightning-arrester and transformer, offer a very high impedance to the high frequency of the oscillatory currents which will usually be set up within the transformer itself when a bound charge within it is released by a stroke of lightning relieving some overhanging cloud. Under such conditions, it is almost as bad to hold back the charge in the transformer as to keep a wave from entering under other conditions.

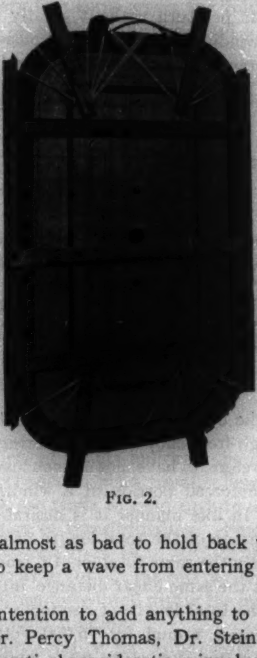


Fig. 2.

It is not my intention to add anything to what has been so ably said by Mr. Percy Thomas, Dr. Steinmetz, and others regarding the theoretical considerations involved in this problem. I simply wish to explain how a theory, that very little preventive reactance is necessary to protect the winding of a transformer whose outer turns are heavily insulated, has been carried out and tested on a large scale during the last four years.

The idea was naturally first put into practice in connection with large high-voltage transformers, but it has been gradually extended, although not so thoroughly, to smaller units operating on pressures as low as 10,000 volts. Thin coils, wound with one turn per layer of flat conductor, such as are commonly used in all the better sort of large transformers, are best adapted to such reenforcement of the insulation between turns.

It is practicable to reenforce a considerable portion of the turns of a large transformer coil so that it will withstand from 2,000 to 20,000 volts per turn without greatly decreasing the space-factor of the winding or causing any considerable increase in cost. It is not practical to use as heavy insulation as this in small units, but, as the size decreases, the length of a turn also decreases, so that the difference of potential between two turns due to a given high-frequency wave is correspondingly less. One should aim, therefore, to have, not a given insulation strength per turn in this reenforced portion of a winding, but a given strength per foot. In like manner it is desirable to reenforce, not the same percentage of the total length of conductor in all cases, but more nearly the same total length, since a given wave will penetrate about the same linear distance into a transformer winding whatever the total length of conductor may be.

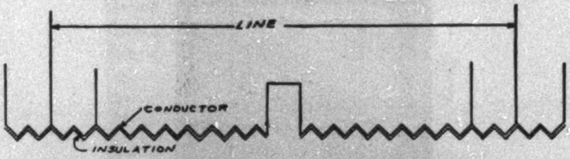


DIAGRAM OF TRANSFORMER WINDING SHOWING TAPS FOR DIFFERENT VOLTAGES BROUGHT OUT NEAR THE ENDS OF THE WINDING

FIG. 3

In large transformers wound for 75,000 volts or less, it is practicable to resist a high-frequency wave whose magnitude is equal to the working voltage in some hundred feet or less of conductor. This means that a wave-length of 200 ft. or more, corresponding to a frequency of, say, 5,000,000 cycles, could be taken care of by such a transformer. If, in addition to this reenforcement, the transformer has an external reactance of some 50 ft. in length, a very considerable reduction of potential between the first few turns will result.

Figs. 1 and 2 show a coil of a 2000-kw. 60 000-volt transformer in cross-sectional and side view respectively, which has such tapered reenforcements of the insulation between the outer turns. The cross-section clearly shows the three different thicknesses of spacing insulation between turns, and the side view of the coil on the form on which it was wound shows the extra insulating on the very first turns where the voltage is likely to be more than could be economically insulated against by spacing insulation only.

The evident desirability of limiting the reenforced insulation to as short a length of the end portions of the winding as will accomplish the desired results indicates the need of a different location of tap connection than usual. Few transformers for transmission work are made without taps to admit of operation with different ratios of transformation. Frequently, such taps cover a range anywhere from 10 to 30% of the winding, and, if they are located so as to cut out the end portion of the turns, the insulation must be reenforced well within the inside tap or perhaps some 40% of the total winding.

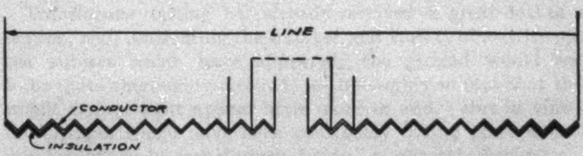


DIAGRAM OF TRANSFORMER WINDING SHOWING TAPS FOR DIFFERENT VOLTAGES BROUGHT OUT NEAR THE CENTRE OF WINDING AND REINFORCED INSULATION AT ENDS

Fig. 4

It has been our practice for some years, therefore, so to locate tap connections that they will cut out centrally located turns instead of end-turns, thereby not only placing them in an essentially safer position, but also avoiding the necessity of any more reenforcement than is required when all the winding is in service.

Some 750,000-kw. capacity of transformers embodying these ideas, ranging in size from 300 to 7500 kw., and wound for 5000 to 80,000 volts have been built in both air-blast and oil-immersed types. Most of these have been installed with a small protective reactance, but many without such protection; and not one of these transformers has yet failed from any weakness of the internal insulation, although a considerable proportion of the transformers has been installed for three years.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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NOTES ON TRANSFORMER TESTING

BY H. W. TOBEY

Transformer testing has already received a great deal of attention, and, considering the number and variety of articles upon the subject which have appeared, the ground would seem to be quite thoroughly covered, so thoroughly in fact that there would at first sight appear little more to add. But in view of the changes which have been constantly taking place and the rapid advance in transformer design, a general discussion of the subject at this time may be of value. Experience also has led to the adoption of certain methods in commercial transformer testing which for various reasons have proved satisfactory, so that a description of these with their advantages and shortcomings will perhaps prove of some interest.

Present methods of testing, like many other methods, are the result of gradual but constant development, in which the good has been as far as possible retained and the poor eliminated and replaced with something better. What was suitable for small transformers, for example, was found to be entirely unsuitable for large sizes, and methods which applied very well to transformers of low voltage had to be modified or entirely abandoned for high-voltage apparatus.

Generally speaking, it may be said that tests are required for the purpose of determining the chief characteristics of the finished apparatus, thus enabling it to be compared with the original calculations and designs, and with the guarantee. They may be classified as follows:

Conversion.
Polarity.

Resistance.
Copper loss.
Core-loss and exciting current.
Regulation.
High potential.*
High voltage.*
Temperature rise.

Conversion. This test, while a comparatively simple one to make, is nevertheless extremely important, particularly where the transformers under consideration are intended for parallel operation or for delta connection to three-phase lines.

The most satisfactory method is without doubt one employing a standard multi-ratio transformer and a single voltmeter, provided the potential of the source of current supply does not fluctuate. Then, by applying a suitable common voltage to the high-tension side of the transformer under test and the standard, the two low-tension voltages may readily be compared and the true ratio obtained.

Where the supply is at all unsteady or where the ratio of the standard varies considerably from that of the transformer under test, the two-voltmeter method is preferable. Accurate results may then be obtained by taking two sets of simultaneous readings, between which the instruments are interchanged to eliminate any dissimilarity between them.

The opposition method is also sometimes used to good advantage. With this, however, care should be used to see that the low-tension voltage of the standard and of the transformer under test are exactly in phase.

As an additional precaution, single-phase transformers which are required to operate in parallel on single-phase circuits, or delta on three-phase circuits, also delta-connected phases in three-phase transformers, should be connected as they are eventually intended to operate, and a test made for circulating current. This serves as a check on conversion measurements and is important from the fact that a slight difference in voltage between windings is apt to lead to serious results.

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*Both of these are essentially insulation tests. The terms "high potential" and "high voltage" are used arbitrarily to distinguish between a test applied between primary and secondary windings and iron, and one applied across terminals of the same winding. The first tests the strength of the insulating barriers and casing, while the second tests the insulation between turns and between layers.

Polarity. The relative positions of primary and secondary leads is ordinarily determined either by direct comparison with a standard transformer; or by applying direct current to the high-tension winding, noting the position of positive and negative connections by means of a direct-current voltmeter, then shifting the voltmeter leads to the low-tension winding and noting the voltmeter deflection upon breaking the direct-current circuit. When testing large numbers of small transformers having approximately the same voltage and ratio, the first method is quicker and more satisfactory. For power transformers having as a rule widely differing voltages, the second method is usually preferable.

Resistance and Copper Loss. In the measurement of resistance for the determination of copper loss and total resistance drop, the fall of potential method gives in general the most satisfactory results of any of the standard methods. The instruments required are less delicate than the galvanometer used in bridge measurements, may be readily calibrated, and give accurate results over a wide range.

When measuring resistances of small transformer windings, the instruments come to rest very quickly and little time is required for taking the readings. With large transformers, however, unless special precautions are taken, this is seldom true; for even with the terminals of the opposite winding short-circuited on themselves, some seconds, or even several minutes, often elapse before the instruments settle, so to speak, to a final value, and, until this settling has stopped, readings do not indicate the true resistance.

Fortunately, this condition of affairs may be overcome by forcing through the winding under test a direct current of ten or twelve times that finally required for the measurement, and after a moment or two dropping it to normal before taking the reading. (Of course during the passage of this increased current the voltmeter should be disconnected and the ammeter short-circuiting switch closed.)

While a delay of a few seconds or several minutes may do no particular harm at the time when cold-resistance measurements are made, it is extremely annoying during heat runs where measurements are taken at frequent intervals. Long interruptions of the load under these conditions are apt seriously to affect the final temperature.

Core-Loss and Exciting Current. The influence of wave-form upon core-loss and exciting current has already been carefully investigated, and the importance of using a sine-wave source of current supply is well known. It is doubtful, though, if all fully realize how far from a sine wave the electromotive force of some generators really is under actual conditions of test; that is, when supplying core loss to transformers. This may occur, even though the wave-form of the generator is entirely satisfactory under normal conditions, from the fact that the wave becomes badly distorted at low power-factors which occur when transformers, particularly those designed for low frequencies, are operated on open circuit. The extent to which this distortion may reach, and its effect on core-loss and exciting current are clearly indicated in the accompanying curves and data which follow.

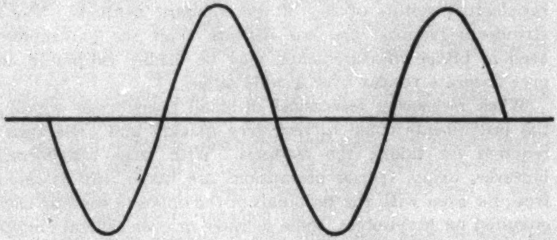

FIG. 1

The curve, Fig. 1, was taken on one of the generators in question while on open circuit. The curve, Fig. 2, was taken on the same machine while furnishing core-loss and exciting current to a transformer. It will be noted that both approximate very closely a sine wave. The oscillograph curve shown in Fig. 3 was taken while a generator, having a very peaked wave, was exciting the same transformer at the same voltage. The resulting core-loss and exciting-current measurements are given as follows:

First case; sine wave, core-loss 1177 watts, current 33.5 amperes.

Second case; peaked wave, core loss 924 watts, current 15.4 amperes.

By comparing these sets of readings it will be seen that in changing the source of supply from one, giving very nearly a sine electromotive-force wave, to one giving a peaked wave, the core-loss decreased to 79% and the exciting current to 44% of the original values.

Another transformer, measured under conditions shown in Fig. 3, and again under conditions indicated by Fig. 4, required respectively 5500 and 7325 watts core-loss and 25.3 and 47 amperes exciting current, an increase of 33% and 87% respectively. These readings show the variations which may occur with peaked waves of the same general character.

These figures clearly indicate the importance of referring all measurements to a standard form of wave. At first sight the peaked wave would seem to have some advantages over the sine wave, owing to the lower core-loss and exciting current values which result. After all sides of the question are considered, however, including among other things the effect of wave-shape on insulation strains, etc., a sine-wave electromotive force is undoubtedly the best. And what is equally important, the generator from which the supply is obtained should not only maintain the standard wave-form on open circuit and on non-inductive loads, but also on low power-factor inductive loads; *i.e., under the conditions of test.*

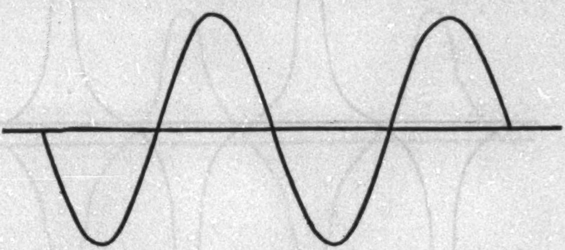

FIG. 2

In the measurement of core-loss on three-phase transformers, the windings across which the readings are taken should be Y connected and the opposite windings left open in case they are intended for delta connection. Otherwise, the circulating current due to unequal distribution of flux in the core and to the short-circuiting of the odd harmonics would show up as an increase in core-loss, thus giving incorrect results. In case the transformer windings on one side are delta connected, and for any reason cannot be changed, it is preferable to connect both sides in delta before taking the core-loss measurement. The resulting circulating current will then occur in two windings instead of one, and, being proportionally less, will produce smaller disturbing losses in the copper than if but one winding alone is delta connected.

Regulation. In general, it is now customary to determine the regulation of a transformer by one of the several methods which require impedance measurements with one of the windings short-circuited on itself, this having entirely superseded the old way of measuring the voltage with transformer free and loaded.

Here, too, it is important to employ a generator which will

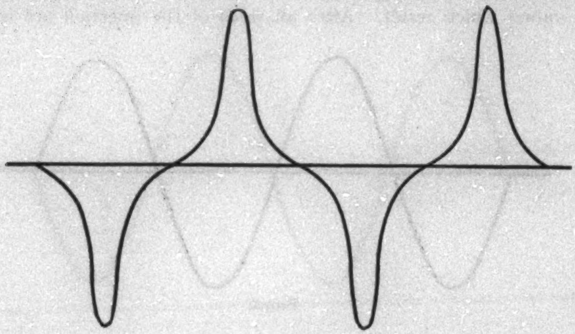

FIG 3

give a sine wave at low power-factor loads, for while it is true that the wave-shape does not affect the measurements so seriously as those mentioned under the preceding heading, nevertheless the variation is fairly well marked.

High-Potential Test. On low-voltage transformers this test is not a difficult one to apply correctly, but where the voltage is high the question is entirely different, and the chance for error is large. This is chiefly because of the absence of a suitable means of measuring high potential. To be sure, either the conversion method or the spark-gap method may be used, though both are open to criticism. Individual conditions alone can determine which is most suitable.

If the testing transformer has extremely close inherent regulation, and the charging current under conditions of test is but a small proportion of its normal current capacity, it is reasonably safe to rely upon the low-tension voltmeter reading, and to consider that this times the ratio of conversion is an approximate indication of the high-tension voltage. If these conditions do not exist, the spark-gap method must be relied upon. It should be used, however, with great care.

As the conditions under which the testing outfit operate are changed entirely by the introduction of the transformer under test, it is obviously not right to measure the high-tension voltage by spark-gap before this transformer is connected. On the other hand, if the transformer is connected in, together with the properly adjusted spark-gap, and the voltage is raised until the latter arcs over, high-frequency oscillations almost invariably occur and result in a rise in voltage. The final value of this voltage may be considerably higher than that required, resulting possibly in an uncalled-for break-down of insulation.

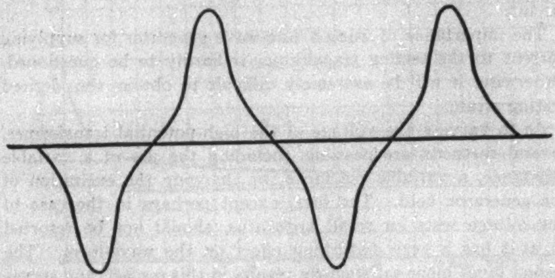

FIG. 4

Such a disturbance may be overcome in one of two ways, both of which have been tried with satisfactory results. The first consists of inserting in series with the gap a high resistance,* the presence of which prevents the occurrence of a high-frequency disturbance when the spark-gap breaks down. The only precaution necessary in the use of this auxiliary resistance is the calibration of the spark-gap with the resistance in series, as its presence will in general increase the effective value of the gap. In other words, the distance between needle-points, as given in the Standardization Rules, may need to be decreased by from 5% to 10% to obtain correct results.

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*For potentials ranging from 100,000 to 200,000 volts, a resistor consisting of a dozen U-shaped glass tubes one-half inch inside diameter and two feet in length will be found satisfactory. These should be mounted in a suitable rack, filled with water and connected in series.

The other method, referred to above, consists in making all connections for the high-potential test and placing the spark-gap across the circuit, the gap previously having been set, however, for a somewhat lower voltage than that required, two-thirds for example. The voltage is then increased, and the low-tension voltmeter reading is noted at the moment the spark-gap breaks. The gap is now disconnected and the electromotive force again raised until the voltmeter reading, in the case cited, is 50% greater than before. The desired potential is thus obtained with fair accuracy without any disturbance in the circuit.

The importance of using a sine-wave generator for supplying current to the testing transformer is hardly to be questioned. Otherwise, it will be extremely difficult to obtain the desired testing strain.

As to varying the voltage of the high-potential transformer, several methods are possible, including the use of a variable resistance, a variable reactance, or changing the excitation of the generator field. The first, except perhaps in the case of low-voltage tests on small apparatus, should not be resorted to, as it has a very disturbing effect on the wave-form. The second gives more satisfactory results in this respect, and serves very well when the required range is not too great. In general, the last method, which is that of varying the generator-field excitation, is perhaps most often used, chiefly because it enables the voltage to be varied gradually over a wide range. Low field-densities, however, are apt to lead to armature reaction if the machine is furnishing anything like full-load current, so that even with this method some distortion of wave-form may result.

A discussion of this branch of the subject would hardly be complete without some reference to the effect which the time of application of the high potential has on the resisting strength of insulation. In other words, if an insulating material will safely withstand 50,000 volts for one minute, what potential will it withstand if the test is continued for five minutes and what will it resist indefinitely?

This relation between time and voltage is fairly well represented by the curve shown in Fig. 5. This was obtained from a series of tests on sheet insulation, potential from a 60-cycle sine-wave generator being applied to two brass discs arranged on opposite sides of the test piece.

It will be noted that for periods of one minute the sample safely withstood a pressure of 65,000 volts. For five-minute tests it was necessary to lower the pressure to about 70% of this value, or 46,000 volts; while, in order to resist the test indefinitely, the applied voltage had again to be lowered to 27,500 or about 40% of its original value.

These figures can hardly be taken as general, for they change considerably with different kinds of insulation and the resulting curves assume widely varying forms. In most cases the reduction in strength as the length of the test increases, is much less than indicated above, so that in comparing the instantaneous test and continuous test, for example, the reduction is nearer 50% or 60% instead of 70% as in the sample noted. These figures serve to emphasize, nevertheless, the undesirability of long-continued strains, and tend to confirm the advisability of retaining the present one-minute standard.

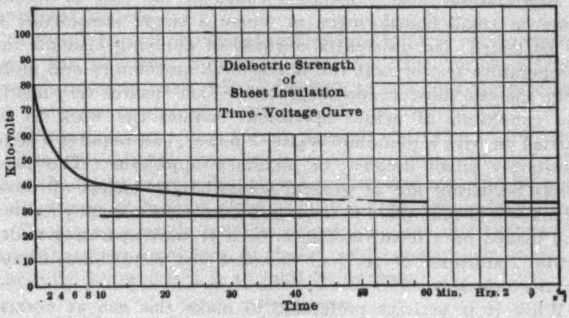

FIG. 5

High-Voltage Tests. The test which determines the strength of insulation between turns, between layers, and between leads, is equally as important as the "high-potential" test just referred to. If the transformer windings withstand double voltage, or, in the case of lighting transformers, triple voltage, their internal condition is reasonably well assured.

In applying this test, it is usually advisable, and in most cases necessary, to use a frequency considerably higher than that for which the transformer was designed; otherwise, the exciting current becomes so excessive as to make it difficult or even impossible to obtain the desired increase in voltage.

In general, satisfactory results are obtained by employing a frequency as much above that for which the apparatus is designed as the test voltage is above normal terminal voltage. With a 60-cycle transformer under consideration, for example, 120-cycle current gives good results for double voltage tests, while 180 cycles is usually satisfactory for triple voltage. A 180- to 200-cycle generator answers very well therefore in the majority of instances.

Temperature Tests. Except perhaps in the case of special tests on small transformers, or where a single transformer is to be tested, the differential method of applying load for the temperature test or heat run is the most satisfactory and probably the one most universally used. This ensures very nearly the conditions of actual operation, enables the work to be carried on with a minimum waste of power, and requires a comparatively small amount of auxiliary apparatus. The total losses occurring are in general somewhat in excess of those which would take place if the transformer were normally excited and loaded on a dead resistance, or if it were operating under actual conditions of service, therefore the results are always on the safe side.

While it is perhaps preferable to make this run at normal frequency, both on the exciting and loading side, still this is not absolutely essential to satisfactory results. In fact, two entirely different frequencies may be employed if desired, it merely being necessary to adjust the exciting voltage so as to obtain what has already been found to be the true core-loss at normal frequency and then to feed the required current into the other side. (By normal frequency is meant the frequency at which the apparatus is intended to operate).

The resistance readings, taken at intervals during the run for the purpose of temperature determinations, should obviously be made with the shortest possible delay in view of the necessary removal of load at such times. It is here, therefore, that the precaution mentioned under the subject of " Resistance and Copper Loss " is most useful. By observing this, and by employing a suitable arrangement of double-throw switches to which the measuring instruments and source of direct-current supply may be permanently connected, the time required to take a resistance reading is reduced to a minimum.

General. The order in which tests should be made depends more or less upon local conditions, so that no fixed rule can be given, nor, in fact, is one necessary. The general order in which the tests have here been described is perhaps as good as any. It has the advantage of placing the heat run at the end, so that, in case any part of the insulation has been injured by previous tests, the fault becomes evident while the transformer is under load and operating under service conditions. It is sometimes considered advisable, however, after the heat run has been finished, to repeat the measurements of core-loss and exciting current. Any defect in the winding then becomes apparent at once.

The question of instruments with which to carry on the various tests has not been touched upon, for this forms a complete subject in itself. It is needless to say that the selection of instruments should be made with the utmost care, as on their construction and accuracy depends the value of the tests.

Not only should they be selected carefully, but the same care should be exercised in their handling and use, and frequent calibrations, at least as often as once a week, should be the rule.

Testing as a whole requires painstaking and constant study, and changing conditions of design and construction must be carefully followed if it is to fulfil its purpose.

DISCUSSION ON "CHOKE-COILS VERSUS EXTRA INSULATION ON THE END-WINDINGS OF TRANSFORMERS," "PROTECTION OF THE INTERNAL INSULATION OF A STATIC TRANSFORMER AGAINST HIGH-FREQUENCY STRAINS", AND "NOTES ON TRANSFORMER TESTING", AT NIAGARA FALLS, N. Y., JUNE 26, 1907

S. M. Kintner: I have tried to make clear in this paper that, for a given expenditure to safeguard against transformer interruptions caused by line surges, more can be accomplished by the use of choke-coils and transformers with reasonable insulation than by adding extra insulation on the end-turns of the same transformer and omitting the choke-coil. It is not my contention that an inferior insulation can be used when choke-coils are employed and satisfactory service got with such an arrangement. Reasonable insulation on transformers of 1000 kw. and upward should be able to withstand from 5000 to 8000 volts between turns.

A. H. Pikler: At the meeting on December 28, 1906, while discussing the paper of R. P. Jackson on lightning protection, the chairman of the transmission committee said:

> If we must have choke coils, let us put them in the same case as the transformers, and so save the complication in station wiring. Better still, let us do away with them altogether, and put such amount of insulation as may be necessary on the end-turns of the transformers; such amount of insulation as will take care of considerable strain between the end-turns. Then if we use a low-resistance arrester or its equivalent, we shall, I think, have ample protection.

This was the first time I had heard advocated such principles. They must have been considered of particular importance and interest because this very subject is treated in two papers of the present convention. Mr. Kintner recommends the use of a choke-coil within the transformer tank, with no extra insulation on the transformer winding; Mr. Moody recommends the extra heavy insulation of the end-turns, and considers the choke-coil superfluous.

From the points of view of both the designer and the operator or station man, I consider the application of either scheme a retrograde step. In designing we should strive for simplicity in construction. The transformer is a simple and classical piece of standard electromechanical apparatus; to use part of the transformer to perform a duty entirely different from that of transforming and transmitting of electrical energy, viz., the duty of the protective apparaus, endangers the simplicity of transformer construction, and both the transformer and the choke-coil would eventually suffer. This is true whether the choke-coil be within the transformer tank and no extra insulation is used on the transformer coil, or the choke-coil be made an integral part of the transformer by putting extra heavy insulation on its end-turns. From the point of view of the station man, I should expect the protective apparatus to protect the main equipment even at the cost of destruction of the protective apparatus itself.

Therefore I recommend the use of the choke-coil outside of the transformer tank, and also extra insulation on the end-turns of the transformer; but the extra insulated end-turns not at all intended to take the entire duty of the choke-coil. Then if something must break down, it will be the choke-coil outside of the transformer tank. Its cost is only a few per cent. of the cost of the transformer, and the interruption of operation of the power plant will last not more than a few minutes, whereas if the choke-coil is inside the tank, either as a separate piece of apparatus or as an integral part of the transformer, this interruption may last for hours or even days.

We all know that in the case of resonance; that is, when the periodicity of the disturbance, the induction, and capacity coefficient have the following relation:

$$2 \pi \sim = \frac{1}{L C}$$

then the phase displacement will have the value

$$\phi = 0$$

and the rush of current will be impeded only by the ohmic resistance

$$I_{max} = \frac{E}{R}$$

and a breakdown follows.

This is what Dr. Steinmetz had in mind when he perpetrated the conundrum: "When is a choke-coil not a choke-coil?"

P. M. Lincoln: I am of the opinion that the choke-coil in connection with high-voltage transmission and high-voltage transformers is a perfectly logical piece of apparatus to use, and the reasons for its use, I believe, are completely, although briefly, set forth in Mr. Kintner's paper and the other papers which deal with the subject. I do not believe we can emphasize too much the value of the choke-coil, owing to the fact of the adjacent turns of the choke-coil having no voltage continually applied between them, as is the case in the transformer. When we come to analyze the matter of putting extra insulation on end-turns of the transformer, we find that it means usually considerably more than is indicated by the paper which was presented by Mr. Moody. Transformers are specified often not only to run upon full voltage, but also to run upon half voltage; also they are frequently specified to be able to run with a delta connection for one high-tension voltage, and a star connection for another; and further, they are often specified to have a range in ratio of 10 or 20 per cent. Therefore, virtually all the taps have to be end taps, with the result that we have to extend that heavy insulation practically from one end to the other. If, therefore, we can take a separate piece of apparatus, such as a choke-coil, and design and install that so that all of these heavy surges which come in can be developed across the turns of the choke-coil, we can thereby save considerable in the transformer and also protect the apparatus to a greater extent.

J. W. Fraser: Looking at this subject from a commercial point of view, I believe that the size of transformers should have something to do with this question. We have on our system, for instance, forty small sub-stations, varying in capacity from 600 kw. to 3000 kw., and will ultimately have a great many more. We practically install four sizes of transformers: 200 kw., 300 kw., 500 kw. and 1000 kw. If we should design each sub-station for large oil-insulated choke-coils, the building would cost considerably more, and the coils would cost nearly as much as a spare transformer. So we have decided to use the coil with large impedance in generating stations where the cost of the transformer warrants it, and comparatively small air-insulated choke-coils, say 20 or 30 turns, in our sub-stations. We make the small choke-coils ourselves at a very small cost. By keeping one or two spare sub-station transformers of each size in stock at some central point of our system we eliminate any chance of a long shutdown.

W. N. Smith: I am disposed to agree with Mr. Kintner in the matter of having separate choke-coils outside the transformer. The tendency toward standardization would naturally incline us toward simplified transformer construction. I look forward to the time when companies operating large transformers will treat them as they do generators, and make their own repairs when they burn out. It frequently happens that when a large transformer burns out, it has either to be sent back to the factory, or an expensive corps of winders has to be sent to the point where it happens to be located. The simpler the transformer coils can be made, the less will be the necessity for such an expensive repair operation. When it is possible for a large power or lighting company with several sizes of transformers to carry in stock a minimum number of standard transformer coils for repairs, economy will result. Viewed from this standpoint, the employment of separate choke-coils will tend toward the standardization of transformers. I also believe it is desirable to have the extra protection of choke-coils for other things than the transformer itself, particularly in a sub-station. Lead-covered cables are extremely sensitive, and as liable to break down as the winding of a transformer, and I believe that the choke-coil is of considerable use as a general protective device in preventing destruction of cables where used in the outside portions of the transmission line, as well as in power houses and sub-stations.

It may be impossible to devise standard choke-coils applicable to all conditions; but as another speaker has said, the power companies are perfectly able to devise them to suit particular conditions.

Another point to consider is the location of the choke-coil in the circuit. That depends to some extent upon the construction of the choke-coil whether it is mounted on a wooden support or porcelain insulators or immersed in oil in an iron case. As surges frequently jump across from a transformer or choke-coil to the iron of the containing case, and can thus make destructive short-circuits, the position of the choke-coil in the circuit should be such that there is some protection outside of it in the shape of fuses or circuit-breakers, particularly if it is to be confined in an iron case. While a believer in the choke-coil, I desire to call attention to this problem of so placing it that a possible short-circuit from some part of it will not cause more damage than it is intended to prevent.

Charles W. Stone: One thing not yet considered is that in one instance a long overhead line was carried into a distributing station, and from this station underground for a considerable distance. In this distributing station lightning-arresters with multiplex connections and choke-coils were installed; the idea being to keep any disturbances which took place on the overhead line away from the cable system. It was found that disturbances occurred in the cable system, and on account of the installation of choke-coils were prevented from discharging across the multiplex connections of the lightning-arresters. Therefore in this case it would be better to have eliminated the choke-coils. The other alternative would have been to put in two sets of static dischargers; one on the overhead line, and one on the cable system, which would have added considerably to the expense and complication. Of course if a choke-coil is placed in circuit and is air-insulated and has a comparatively few number of turns, it might be possible that high-voltage disturbances on the cable system would jump across the turns of the choke-coil, and discharge themselves across the multiplex connections of the lightning-arresters, as just explained by Mr. Berg.

E. E. F. Creighton: I have attempted to make laboratory measurements on choke-coils to determine some method by which we could choose their dimensions, and I think we shall have to go back to the fundamentals to find out just what the choke-coil is for. With Mr. Berg and Mr. Stone, I think that the choke-coil is sometimes disadvantageous. The function of the choke-coil is to prevent or to hold back high-pressure high-frequency surges long enough to permit the lightning-arrester to get into operation. Every lightning-arrester in operation to-day has a certain dielectric spark lag; that is to say, after the potential is applied to the lightning-arrester there is a brief interval, a few millionths of a second, before the lightning-arrester begins to discharge and lower the voltage on the system. If there is no choke-coil between the lightning-arrester and the transformer, the end-turns of the transformer receive this high potential strain during the interval that the lightning-arrester is getting into operation. These high-frequency disturbances nearly always come from an external source; consequently the practice has been to place the lightning-arrester on the outside of the choke-coil. If the lightning is internal, the choke-coil is then more or less disadvantageous according to its value in inductance. One solution of that problem is to use a large inductance in a choke-coil and to place lightning-arresters both inside and outside the choke-coil. A laboratory experiment demonstrates these statements.

The disrupted discharge method is used with the following apparatus: two choke-coils representing the two choke-coils in the line, a spark-gap on the outside of the choke-coils, on the side the disturbance is coming from, and another spark-gap on the inside of the choke-coils.

The circuit can be better illustrated by Fig. 1. The outside gap is in the location of the lightning-arrester. Now produce a discharge on the outside; set the outside gap so that it will spark, and the spark at the inside gap is comparatively small and weak. On the other hand, open the outside gap until the potential can no longer bridge the gap, and the potential on the inside gap will rise to such a value as to give a spark more than twice as long as the outside gap. On one test, the outside gap was not sparking with a setting of one inch, and the inside one was sparking with a setting of two and one-half inches.

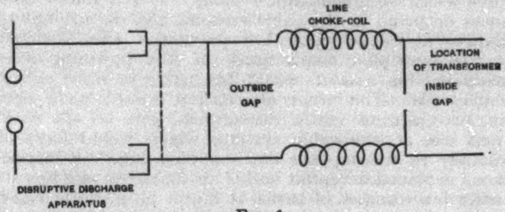

FIG. 1

It seems to me that is sufficient proof, either that this choke-coil should be protected on the inside, or the choke-coil made small enough so as not to magnify the potential on the inside. It is usually a difficult matter to explain just why higher potentials occur on the inside. In this case, of course, the potential came from the outside.

An experience I had last Friday would perhaps be of interest, showing that even with very high values of inductance the transformer cannot be protected from the high potentials. In making some tests on insulators to determine the gap necessary to place on horns in parallel with the insulator to protect it, a condenser was placed across the transformer operating at about

75,000 volts. After three or four strokes, the transformer insulation broke down inside, and on making an examination of it we found it was not the end-turns which were affected, but the third coil down from the end. This transformer is designed to operate at 100,000 volts, and has been used for hundreds of thousands of discharges. We have, however, always used a protective device in connection with it. In the test I refer to it was used without protecting device. In that case you can see there must have been some combination of inductance and capacity giving a resonant condition, which produced high potential very far internally in the transformer. The subject is not simple.

William McClellan: I have advocated external choke-coils and shall continue to do so until there is produced a good low-resistance lightning-arrester with the attributes of an ordinary safety valve; in other words, until the potential at the transformer terminals can be kept practically constant. Extremely low-resistance fuse-arresters work quite well, but they are not self-renewing. Certain types of the horn arrester have given some satisfaction, but they are uncertain. The real question is not so much shall an external choke-coil be used, but shall it be a simple air-insulated coil of a few turns, or an elaborate oil-insulated coil in separate case.

W. S. Lee: As an operating man I am in favor of both choke-coils and extra insulated end-turns. I am continually trying to improve the lightning protective apparatus by putting on first one kind of choke-coil, and then another. Our company is in favor of heavy insulated end-turns and want them on all transformers, for in practical operation, when lightning from the line strikes into the end-turns, we usually find that it goes to the case at entrance to transformer, or burns the terminals off. As Mr. Fraser has told you, we have in the neighborhood of forty stations on our line, grouped about at different places. Some of these stations operate a group of cotton mills that owns the station. We have attempted to put protective apparatus at all of these places but it is not easy to get the mill owners to invest in expensive choke coils. However, in our large plants we are installing the choke-coil and getting satisfactory results.

R. P. Jackson: Mr. Moody's statement, that the disturbance is likely to proceed into the tansformer some distance in feet, is, in a way, aproximately true. I think, however, that a better way of measuring the penetration disturbance would be in henrys. Tests I have made indicate that disturbances of the commoner kind will penetrate into the transformer windings, roughly, about 0.04 to 0.06 henrys. A choke-coil of that value put outside the transformer will cause the disturbance to be absorbed or reflected, and very little will go through into the transformer. That value for a choke-coil, 0.04 henrys, is pretty high for a small transformer of low voltage, but insignificant for a high-voltage transformer.

In a paper read by me before the Institute last December, a curve was given indicating that a zero choke-coil would reflect a zero surge, and that the larger the choke-coil the more surge was reflected, with a descending curve something like a logarithmic curve. About 30 per cent. of the disturbance would penetrate through a coil of 0.04 to 0.06 henrys, while very little additional gain was to be obtained by increasing the size of choke-coil. At that point, about 70 per cent. of the surge was reflected, or failed to appear any farther in the windings, so it would seem that if extra insulation were to be put on the proper number of end turns to get safety, we should cover approximately the number of henrys previously given; or 0.04, not considering the iron, which would be a reasonable amount for this extra insulation to be placed upon.

I doubt if any harmful effect from choke-coils occurs very often. The damage to a transformer as the result of switching is usually the result of a sudden change of potential at the terminal of the transformer. Mr. Tobey's paper indicates that the breakdown of the spark-gap at the terminal of the transformer causing a breakdown of the insulation between the turns, is simply a case where the terminal suddenly dropped in potential while the rest of the transformer winding had a comparatively high potential; the result was that the charge on the interior windings attempted to get out at the point of low or zero potential, resulting in a breakdown between turns. A choke-coil at the terminal of a transformer will simply make this change of potential at the terminal more slow in occurring; that is to say, this sudden change occurs at the terminal of the choke-coil instead of at the terminal of the transformer, so that unless the cases are very special—something I have not encountered—the disturbances, whether from the inside or the outside, will be dampened out; their effect on the transformer will be much less if there is a choke-coil of some appreciable inductance than if there be no choke-coils. In other words, the disturbance reaches some distance into the windings from the end or terminal, whether this be the terminal of the transformer, or of the choke-coil.

If the electrolytic lightning-arrester makes good its promise, I think there will be a fair chance of either omitting the choke-coil entirely or making it much lighter, because the electrolytic arrester will be able to keep the potential to a fixed point at the terminals of the transformer.

"When is a choke-coil not a choke-coil?" was, I believe, propounded by Dr. Steinmetz sometime ago. This conundrum has very little bearing on practical matters. If the frequency is so high that, due to condenser effect, it will go through a choke-coil, it will also go on through the transformer for the same reason, and do no damage in either case, so that then one can truthfully say that when a choke-coil is not a choke-coil, there is no need of a choke-coil.

C. P. Steinmetz: The purpose of the choke-coil is to protect the station apparatus against the entrance of high voltage. Therefore, the choke-coil must be between the apparatus to be protected and the source of high voltage, that is, the transmission line as the main source. The choke-coil must therefore be immediately at the transmission line, next to the lightning-arrester. As a good and convenient location for the choke-coil, I recommend the transformer tank. That means, however, that the transformer must be the first piece of apparatus on the transmission line. This is seldom the case. Frequently a number of transformers feed together into high-potential bus-bars and a number of transmission lines are operated from the same bus-bars. In that case, then, we have the transformer switches between the transformer and the high-potential bus-bar, and the feeder switches between the bus-bar and the transmission line. Now, these high-potential bus-bars, the transformer switches, the feeder switches, the current transformers, the connection of the potential transformer —all must connect in between the choke-coil and the transformer; otherwise these different pieces of apparatus are not protected by the choke-coil. This appears to me rather to make the arrangement complicated and impracticable where the choke-coil is desired in the same case with the transformer. Furthermore, we must consider that the choke-coil receives lightning potential; that is, it requires a much more careful installation than the transformer, and the liability to puncture by discharges jumping across surfaces, etc. at the entrance to the choke-coil is much greater than that with any other apparatus and it appears to me the immediate neighborhood of the choke-coil to other apparatus is just as undesirable as that of the lightning-arrester. To avoid this difficulty one very simple way is to have no insulation but air, and it may then be feasible to put a choke-coil out-doors, up on the poles between the transformer station and the lightning-arrester house, where such exists. In those cases where there is other apparatus between the transformer and line, then in addition to the choke-coil which is on the line we require either a second choke-coil at the transformer, or special protection of the transformer, because the transformer also is a source of high potential, as Mr. Thomas showed us some years ago, and we have to guard against that also. The simplest way is the extra insulation on the transformer, which in this instance appears not as alternative to the choke-coil on the line, but as a protection against self-destruction of the transformer, in addition to the protection afforded by the choke-coils against the entrance of high potential from the outside.

The second point I desire to draw attention to is the curious experiment of Professor Creighton, where at the point beyond the choke-coil the voltage of the disturbance was greatly increased. Let us, for instance, consider the transmission of 10,000 kw., at 33,000 volts, 60 cycles, three-phase 33,000; volts between lines means 19,100 volts from line to ground, and 175 amperes per line. Assuming the choke-coil to consume one per cent. of the voltage, that is, a very large choke-coil, as proposed, this gives a reactance:

$$x = \frac{191}{175} = 1.09 \text{ ohms},$$

hence an inductance:

$$L = \frac{x}{2\pi N} = 2.88 \text{ mh}.$$

This choke-coil is interposed between the line and the station wiring, which station wiring also has a certain electrostatic capacity, though small it may be. That means you have an inductance in series to a capacity.

Estimating the capacity of the station wiring, that means of the connection from the choke-coil to the transformers over the different switches, circuit-breakers, bus-bars, etc., as equivalent perhaps or of a magnitude of something like 50 feet of wire, that would give you a capacity of about

$$C = 0.0002 \text{ mf}.$$

The frequency or resonance of this combination of capacity and inductance in series would then be:

$$N = \frac{1}{2\pi\sqrt{LC}} = 200{,}000 \text{ cycles},$$

approximately. Any disturbance, wave, impulse or oscillation, coming from the transmission line and approaching this combination of choke-coil and station wiring, if of this frequency, or containing a component of this frequency, meets resonance, and the choke-coil generates voltage, raising the voltage in the station to—theoretically—infinity. Well within the range of lightning frequencies is 200,000 cycles; that is, impulses of static induction from the clouds, etc. A large choke-coil even with moderate voltage may build up, due to the inductance of the choke-coil in series to the station capacity, and produce a high voltage, and instead of protecting, the choke-coil so may produce destructive voltages, by resonance with the capacity of the station wiring. That is, a large choke-coil may be a source of danger, and this danger must be kept in view. At much higher frequency, and lower capacity and inductance, this phenomenon was shown experimentally by Professor Creighton: the inductance of the choke-coil in series with the capacity of the connection back of it, raising the voltage of the leyden jar discharge to the much higher value observed beyond the inductance.

The conclusions to be drawn therefrom are that the length of wiring between the choke-coil and the transformer should be as short as possible, and that the choke-coil should be of as low inductance as possible; that is, as low an inductance as will still give a sufficient decrease of the steepness of the wave-front to allow the lightning-arrester to take up the discharge; but not more than that, because any increase beyond that inductance lowers the frequency of resonance and therefore increases the liability of picking up destructive voltages from line impulses. These two conditions should be very carefully adhered to: the lowest possible static capacity of the circuit between the choke-coils and transformer end of the line, and the lowest possible inductance of the choke-coil which still gives sufficient protection, and with these two limitations I also believe in the desirability of the choke-coil between the overhead line and the station, because it decreases the steepness of the wave-front of the incoming wave, and so acts beneficially.

Ralph D. Mershon: I do not care much for choke-coils, unless they are small enough to be put out of doors. In my opinion, choke-coils inside the station make the station wiring very difficult. If indoor choke-coils are used, they should be inside the transformer case; otherwise, I would rather have the end-turns of the transformers insulated to act as choke-coils. It seems to me there is a good deal of needless objection made to insulation of the end-turns in cases where different voltages must be obtained. Mr. Moody shows how voltage taps can be got without interfering with the end-turns, by varying the number of turns at the middle of the winding, instead of at the ends of the winding. It seems to me that in the case of multiple and series connection, to obtain full or half voltage, a somewhat similar course could be followed, and the same end-turns used for the multiple or series connection. Of course, in such cases, the end-turns will have to be made with a carrying capacity sufficient for the multiple connection. In most cases, I do not think this would be a serious matter.

The depth to which the disturbance penetrates a transformer is a matter of frequency. Until we get further data as to the frequencies which actually occur in practice, it seems to me that we cannot make much headway in determining how far the disturbance penetrates.

In regard to Mr. Tobey's paper. in most cases I have found it very difficult to measure the resistance of large transformers by the fall-of-potential method, because of the difficulty of keeping the direct current perfectly steady. It is not always possible to have a storage-battery for such measurements, and the voltage of a generator driven from commercial circuits generally varies enough to introduce serious errors into the measurement. I would like to know what source of current Mr. Tobey uses in this method of measuring the resistance of transformers in the field.

I judge from Mr. Tobey's paper that he contemplates making the resistance test before the temperature test. It seems to me the resistance test should be made after the temperature test and with the transformer at normal temperature. I gather, also, that he has in mind making the final insulation test before the transformer goes out of the factory. Such practice I do not consider as either proper or safe. A transformer might stand 500,000 volts in the factory; but by the time it has been shipped and installed, it might not be able to stand 5,000. What the customer wants to know is what the transformer will stand after it has been installed and under operating conditions, as regards temperature, etc.

I am rather surprised at the dielectric time-voltage curve given in Mr. Tobey's paper. I had no idea that the dielectric strength of insulation in ordinary use diminished so rapidly or diminished to such an extent as he shows. It would be interesting to know the nature of the insulation on which the curves are made. If the curves are correct, it seems to me that we should have more than a double-potential test of transformers.

If the end-turns of transformers are to be more heavily insulated than the rest of the winding, what is the most satisfactory and intelligent way of specifying such insulation? And what sort of a test can be given the transformer to find out that the end-turns have been insulated in accordance with the specifications?

D. B. Rushmore: In any commercial installation, I think there is no question but that some kind of choke-coil should be installed, and, as a matter of fact, always is installed. The problem is, what kind of choke-coil should be used and what amount of reactance should it have.

The choke-coil is of use in preventing the entrance into the station of current from a lightning disturbance on the line. A lightning disturbance usually takes place during a rain storm when the insulators are wet and break down at the lowest point. The transformers are usually insulated to withstand twice the operating voltage. They will withstand that, and as a matter of fact a great many high-potential transformers will withstand three and a half times normal operating voltage before rupture takes place. If any disturbance occurs on a transmission line, it need only be reduced very slightly in order to protect the transformer, if it has not gone over the insulators.

Lightning disturbances are of a very high frequency, as shown by the short distance which they travel before they break over insulators when the voltage is sufficiently high. The suggestion has been made to protect a station by using fine wires leading into the station, wires of such diameter that an increase of voltage of 75 to 100% above the normal operating value will be above the corona effect on the wires, and thus the automatic disturbance will be largely dissipated outside the power station.

W. LeRoy Emmet: In these high potential disturbances operating through inductive circuits, the danger lies in a condition of elasticity. All of these highly insulated circuits are electrically in a perfectly elastic condition. There is no energy dissipation, and consequently, inductance combining with capacity produces a condition equivalent to that of an efficient spring. If these circuits could be made inelastic, they would absorb such vibrations as Mr. Steinmetz describes. With very high frequencies, small capacities, small inductance may create very high local voltages. It occurs to me that in Mr. Moody's arrangement of insulated turns on the transformer, the practical efficacy may lie somewhat in the fact that the insulation has some power of absorbing energy, and so forms a sort of gradient of potential that penetrates the transformer; whereas with a device like a separate choke-coil, incapable of absorbing any energy itself, that gradient does not exist, and a point of high potential may occur beyond the choke-coil. I had one experience which was perfectly definite, where a choke-coil inserted between a line and apparatus, caused repeatedly the puncture of the apparatus and the failure of the lightning-arrester. It was in a certain case where lightning always came the same way and acted the same way on the circuit. When that choke-coil was put in, the lightning made trouble, and when the choke-coil was out, the lightning made no trouble. In such a case we have a vibrating system with conditions very difficult to predict. If we could have inside the choke-coil or somewhere near the terminal of the transformer some means of dissipating energy, something that would absorb the impulses of high period and voltage, it would kill the resonance, and it seems possible that the leakage and dielectric hysteresis in the insulation may do this; local absorption of energy in the iron may also effect the condition. The electrolytic lightning-arrester should be applicable. It seems to me that some effort in these directions might be expected to give good results.

O. S. Lyford, Jr.: There is one important feature of the choke-coil proposition which I have not heard discussed since I came into the meeting. In his list of objections to choke-coils as now used, Mr. Kintner omitted an important objection to a coil of high reactance immersed in oil; namely, the use of additional high-tension terminals carried out through a grounded case. In a high-voltage transformer station equipped with oil circuit-breakers and choke-coils we now have seven or eight such high-tension terminals per phase; two, or possibly three, for the main transformer, one for the series transformer, two for the choke-coil, and two for the circuit-breaker. Insulation failures occur most frequently in the bushings around such terminals, and it is therefore very desirable to minimize the number of such terminals. Putting the choke-coil inside the transformer case, as proposed by Mr. Kintner, is a step in this direction and also takes care of the point which Dr. Steinmetz raised, that the choke-coil should be as near the transformer winding as possible, but it leaves us still in a dilemma, as we have not afforded to the circuit-breaker and series transformer such protection as the choke-coil gives to these devices. Mr. Kintner claims that a choke-coil affords a fixed amount of protection to any apparatus placed back of it and to obtain this protection we desire to place the choke-coil between the line and all other apparatus.

One logical way to take advantage of Mr. Kintner's suggestion and at the same time minimize the number of high-tension terminals and put the maximum amount of equipment back of the choke-coil, is to put the whole outfit, choke-coil, circuit-breaker, series transformer, and main transformer, all in one tank. There would then be only two, or possibly three, high-tension terminals per phase, and all the apparatus except these terminals would be protected by the choke-coil. I believe this is a practicable arrangement and I recommend it for your consideration.

H. W. Buck: This discussion for and against choke-coils sounds a good deal like a conference on the subject of church unity. Every man is setting forth certain dogmatic beliefs which he has for or against choke-coils. One man may have had a certain experience under a certain combination of circumstances with a choke-coil, which has led to the destruction of his apparatus, and for all time thereafter he condemns choke-coils. The next man has had very good success during certain seasons with similar appliances, while he had choke-coils on his system, and for that reason he is equally certain that the smooth operation of the system has been because of the choke-coils. Both conclusions are probably without any ground whatever. The circumstances which lead to surges of potential which bring destructive results to electrical apparatus have an infinite number of combinations: they depend upon the length of the circuit, the number of sub-stations, the size of the transformers, the transmission frequency, the particular character of the country where the lightning stroke took place, the voltage of the line, the conditions of operation at the moment, the load on the line, the question whether any circuit-breakers went out at the moment or not, etc. Under these conditions, in my opinion, it is absolutely impossible to calculate the problem beforehand mathematically, and equally impossible to demonstrate it experimentally. General conclusions can be figured under a given set of circumstances mathematically; or the transmission system can be set for a certain set of conditions, experiments made, and conclusions reached, but as to whether a choke-coil can be condemned as a universally useless piece of apparatus or praised as an apparatus which cures all lightning or surge troubles cannot be decided at the present moment, and in my opinion can never be conclusively decided.

S. M. Kintner: Mr. Pikler apparently misunderstood me when he took the stand that I recommended the use of choke-coils inside the transformer case. I did not offer that as a recommendation, but merely as a suggestion of a means by which some objections made to the use of choke-coils might be overcome.

Professor Creighton has shown the results of an experiment in a diagram upon the board, and quite general conclusions have been drawn from it. I would like to show by a sketch an experiment I made, and state the results obtained. The experiment was quite simple. This was also a laboratory experiment. I arranged the apparatus as shown in the following sketch, Fig. 2.

In this diagram it will be seen that a static machine (Holtz or one of that type) supplies a charge to an insulated sheet of tin which represents a cloud. Directly below this sheet is another, also insulated from earth, which represents the capacity of a transmission line both to earth and to the cloud. The imitation transmission line leads into a metal box which can be considered as representing the power-house building, or even the transformer-case which is always of metal and grounded. Gap A represents the lightning-arresters, while inductance coil *L*, condenser *C*, are representative of the transformer. Spark-gap *B* is a measuring gap and is used in determining the momentary voltage maximums to which the transformer windings may be subjected in strains to ground when charged clouds in the vicinity of the power-house were discharging.

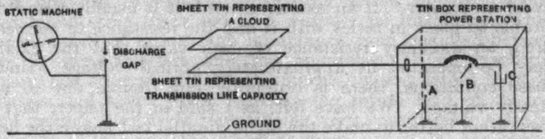
STATIC MACHINE
SHEET TIN REPRESENTING A CLOUD
TIN BOX REPRESENTING POWER STATION
DISCHARGE GAP
SHEET TIN REPRESENTING TRANSMISSION LINE CAPACITY
GROUND
A
B
C

FIG. 2

In brief, the results of the tests showed that gap *B* never discharged when it was larger than gap *A*, and the general conclusion drawn was that a transformer protected by a lightning-arrester would not be subjected to shocks, due to bound charges inside the transformer when they were released by a cloud discharge in the immediate neighborhood, that were in excess of the voltage setting of the lightning-arrester.

W. S. Moody: Of course the purchaser can specify the amount of insulation, or the test that it should be capable of withstanding, but it is hardly practicable to make tests to check this in the finished apparatus. I think the best that can be done in the way of testing is to make up a sample coil with insulation identical to that which will be used in the transformer, and then test the sample. I believe that if we use insulation between layers which will withstand something like 25 per cent. of the line voltage for the outer portion of the winding, we will have a very safe design. Theoretically, a uniformly tapered insulation should be used, but practically, it is out of the question to make more than two or three steps in the amount used. We start with an insulation between adjacent turns or layers that will stand 25 per cent. of the line voltage, and taper this in two or three steps to the normal insulation at a point, say 200 feet, within the winding.

Ralph D. Mershon: To what percentage of the total winding would you give the heavier insulation?

W. S. Moody: I do not think that we can attempt to determine this with any great accuracy. In most transformers 200 ft. should give a length which would absorb any voltage which a good lightning-arrester will not discharge if the voltage is really what is commonly known as high frequency.

H. W. Tobey (remarks made before reading the paper): In the preparation of this paper, the idea was to describe in general some of the more important features of up-to-date transformer testing and also to outline a few of the methods which have been proposed and for one reason or another have been discarded. (Mr. Tobey read the paper, and then replied as follows to various questions):

We find we have usually obtained better results by using a storage-battery for the source of direct-current supply than by using an exciter. If an exciter is used, it is usually found desirable to place in series with it and the resistance to be measured, an auxiliary resistance of such value that the exciter may be operated at approximately normal voltage. Under these conditions, there is ordinarily but trouble due to unsteady voltage. We have felt, as I said in the paper, that it was rather better to make the high-potential test before the heat run, so that in case the insulation was injured by the latter test, the fact would become known during the heat run. There is no other reason, however, why the order of the tests could not be changed if thought desirable.

As to the curve referred to in the latter part of the paper, I may say that it was based on tests made on paper insulation and was purposely selected because it showed a marked difference in dielectric strength between the short time test and the long continued test. The difference is more marked in this curve than we find in ordinary insulation. Usually the change is perhaps 30 per cent.; that is, the dielectric strength would be 30 per cent. less in continued operation than when subjected to an instantaneous test. Attention should also be called to the fact that the sample in question consisted of one thickness only, whereas ordinarily in transformer construction the insulation is made up from a number of laminations so that the factor of safety is well on the safe side.

E. J. Berg (by letter): To me it would seem that relatively small reactive coils and reinforced insulation of the end-turns afford the best protection.

The breakwater analogy used in Mr. Kintner's paper is perhaps as close as any mechanical comparison could be, but it must be remembered that waves are set up on each side of the breakwater and that the apparatus to be protected is located on one side thereof. Consequently, whereas the breakwater affords a good protection for a wave coming from the outside it is objectionable for waves coming from the inside.

Briefly, since not only the line, but electrical apparatus connected to the line under certain conditions that are brought to a very high potential above ground and are suddenly discharged through the lightning-arresters, it is obvious that whereas the reactive coil between the apparatus and the lightning-arrester will afford a protection from the surge which comes from the line, it would be detrimental for the surge which comes from the apparatus itself.

Unfortunately, the inductance and capacity of the electrical apparatus is very small compared with that of the line, or a reasonable section thereof, therefore the frequency of discharge of the apparatus is much greater than the frequency of the discharge of the line. A reactive-coil which has a considerable reactance for the line frequency has an enormous reactance for the surge from the apparatus and therefore may prevent its reaching the lightning-arrester, and may even intensify the voltage.

A practical demonstration of this action of reactive-coils was found some years ago in a commercial installation where reactive-coils of rather high inductance were installed between the lightning-arresters and the apparatus. Upon inspecting these coils after some lightning storms, it was found that discharges had taken place between the inside lead of the coil and ground, discharges representing very considerable voltages. In view of this and the reasons given above, it has seemed best to the writer to use air-insulated coils, which, to be sure, have relatively small reactance, but which are self healing, for excessive voltages they act as an additional number of gaps. The discharge from the transformer being able to reach the lightning-arrester over the turns instead of through them, obviously, insulated reactive coil would not answer in this case.

B. C. Shipman (by letter): The reasons for using a separate choke-coil, as given by the author, far exceed the reasons against it, both in number and force, I think the matter is generally so regarded. To depend on the insulation of the end-turns only, for protection, is hazardous. Even if trouble is escaped in nine cases, the tenth may cause very disastrous results, far outweighing any disadvantages of an additional piece of apparatus, or complexity in wiring. If it be granted that the choke-coil performs the service expected of it, it seems to me to be better engineering to hold up excessive surges and potential strains outside of a transformer, rather than to admit them and then attempt to withstand them by extra insulation. Injury to a choke-coil is comparatively unimportant; to the transformer it is serious.

The reactance of the turns of the transformer-coils themselves will vary according as the transformer is open-circuited on the secondary or not; if not open-circuited, with the load connected. In the latter case, the reactive effect of the primary being less, the extra insulation would have to extend farther into the coil than if the secondary were open-circuited. I recall one instance where three 2000-kw. transformers were connected to the transmission line, but only two were supplying current from the secondaries, the third being open-circuited. A lightning disturbance entered the station, and, passing the protective devices, broke down the insulation between turns of the idle transformer, while it left the working transformers uninjured. This I attributed to the greater choking effect of the idle transformer, causing a steeper gradient of voltage in its coils.

Regarding the advisability of putting the choke-coils in the same case with the transformer, it might be desirable in certain instances for special reasons, but in general I think it would be bad practice. There are enough complications now in a high-tension, multi-tapped, water-cooled transformer, and the interior is hard enough to get at without making it more so.

I agree with Mr. Moody on the desirability of reinforcing the end-turns of transformers, not, however, to take the full force of the extra strains, but to be able to withstand whatever portion of such strains that passes the choke-coils.

Frank G. Baum (by letter): It has been my experience that trouble due to lightning rapidly disappears as the insulation of line and apparatus improves, and when the insulation becomes what it seems it should be, the lightning trouble practically disappears. That lightning trouble is largely a matter of insulation is proved by the fact that, where 15,000-,25,000-, and 60,000-volt lines all pass through the same country, the trouble generally appears on the lower voltage lines. I doubt very much if a first-class insulator will be punctured even by a lightning bolt striking the tower, because it would seem to be very much easier for the lightning to go to the structure direct.

In the protection of a line against lightning in the section of the country where very severe lightning is prevalent, it is not a question of one method versus another, but all the precaution that can be taken at reasonable expense. In some sections extra insulation could be used, on the transformers, choke-coils externally, lightning-rods or ground-wires on certain sections of the line, also horn gaps at certain places to protect against high surges, these horn gaps probably having some resistance connected to ground. It is quite certain, however, that on a high-voltage, high-power transmission system the ordinary spark-gap arresters are useless.

A. C. Pratt (by letter): I believe thoroughly in the desirability of providing extra insulation on the outer turns of a static transformer and placing the taps for voltage adjustment near the middle of the windings. I advocated this method in 1904 in discussion of a paper by Mr. Moody and brought out the further advantage that in case the transformer is operated with less than the total high-tension winding in service, the maximum pressure to ground from the outer turns of the winding is normally never more than that from line wire to ground, which is not the case if the taps are next the outer terminals of the winding.

After eight years' experience and observation on lines operating at from 10,000 volts to 60,000 volts, I am in favor of separate choke-coils in all ordinary cases, and for substantially the same reasons as set forth by Mr. Kintner; I would however favor somewhat heavier insulation between the outer turns of the transformer than between the inner turns, as the outer turns are doubtless often subjected to quite severe strains due to switching and to the inability of the choke-coil to afford complete protection under all conditions. There seems to be no doubt as to the ability of the choke-coil to afford a very large degree of protection.

James Lyman (by letter): The resistance offered to a line disturbance depends directly upon frequency. The frequency of a surge, whether from a short-circuit, ground, or lightning discharge, may be anything from the normal frequency of the line current to a million cycles per second. If the frequency is low, as is the case with many induced lightning charges, the choke-coil offers practically no resistance. Therefore, the transformer windings should be insulated to stand such strains as will not readily be discharged over the lightning and static arrester. A form of choke-coil consisting of 20 to 50 feet of solid copper conductor wound on mandrels 5 or 6 in. in diameter with 0.25 in. air clearance between turns, takes practically no extra room and offers considerable resistance to high-frequency discharges. Extra insulation to the outside turns in high-tension transformer-coils is also recommended as an additional protection against abnormal voltage caused by high-frequency disturbances. The added insulation does not materially increase the size of the transformer, but taken together with the small choke-coils and lightning and static arresters of a reliable design give the most satisfactory results. Where choke-coils of 400 ft. of conductor have been installed between the lightning-arrester and transformers, instances of discharge across the transformer-coils have occurred, indicating a rise in voltage due to the reactance of the choke-coil in preventing the discharge of the transformer. It is my opinion, therefore, that large choke-coils are not always a protection, and, considering other objections to them, they should not be used.

Farley Osgood (by letter): I think it is better to keep the insulation of the transformer as nearly the same throughout as possible, as it saves expense and saves space in the transformer case. I can see no reason for insulating the choke-coil unless it is to be placed in a position where there is insufficient room to carry bare copper, and, generally speaking, the position would not be a good one for any high-tension equipment. If the choke-coil is made without insulation, its perfect condition or damaged state can be quickly and clearly seen, which might not be the case with an insulated coil.

The proper position for choke-coils is in the high-tension chamber, where there should be sufficient room as to make the matter of this slight additional equipment, which virtually requires no attention, of very little consequence from a complication standpoint.

My experience has been that choke-coils are a real benefit on voltages of 33,000 or greater, and, therefore, the use of the coil is recommended in all cases.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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NOTES ON RESISTANCE OF GAS-PIPE GROUNDS

BY J. L. R. HAYDEN

Earth connections in electric circuits are frequently made by driving a gas pipe into the ground. Such grounds are of fairly high resistance, and therefore not permissible where a low resistance ground is required. Their great simplicity and cheapness makes them desirable, where very low ground resistance is not necessary, as for discharging static charges, earthing overhead ground-wires, etc. To get data on the resistance offered by such gas pipe grounds, their permanence, and the variation of the resistance with the seasons, an investigation was started two years ago.

Three gas pipes of 2.5 in. diameter were driven into the ground at distances of 15.75 ft. between I and II, and 7.4 ft. between II and III, in the lawn adjacent to Dr. Steinmetz's laboratory. The soil is a clay loam, overlaying shale rock a few feet below the surface. The pipes are driven into the following depth:

I. 3.75 ft.
II. 2.75 "
III. 3.10 "

The resistance of the three grounds was measured with an alternating 60-cycle current of 120 volts, and as return ground was used the system of the city water pipes. This return ground showed to be less than 0.01 ohms. It was therefore neglected.

Readings were taken at irregular intervals from August 1905 to August 1906, and daily from September 1, 1906 to date: during fall and spring, morning and evening readings were taken to see whether the daily temperature variation had any effects. These however, were found so small that in the attached curves the daily average has been used.

Fig. 1 shows the variation of the three ground resistances during the whole period, and Figs. 2 and 3 the variation from September 1906 to date, in larger scale, so as to show the daily values. The values are given in amperes at 120 volts 60 cycles, and so are proportional to the conductivity.

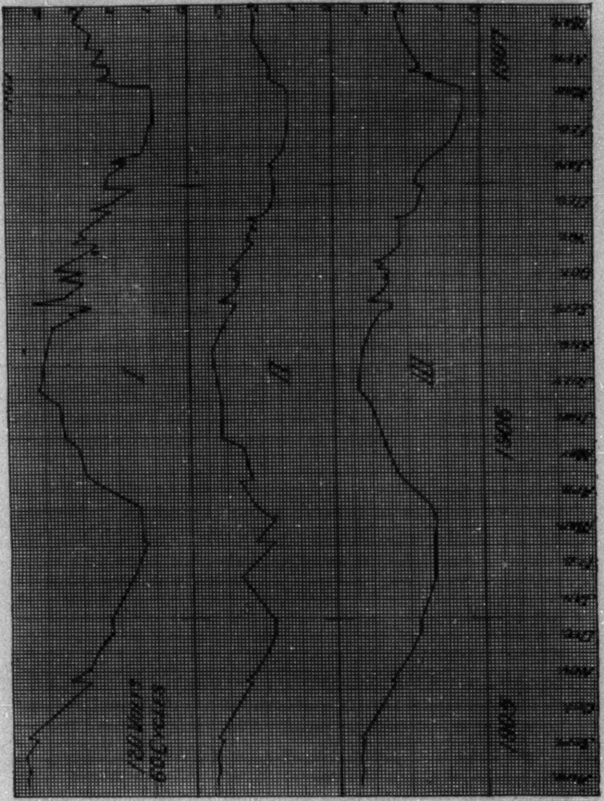

FIG. 1

The lower curve gives the daily average of temperature, and the rain fall, the height of the black line giving approximately the intensity of the rain fall.

The curves show very plainly the sudden rise of conductivity

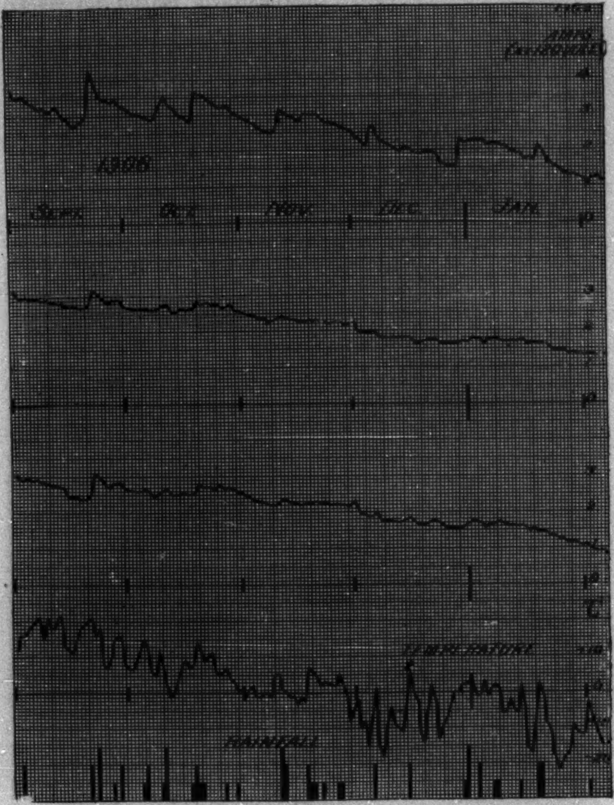

FIG. 2

at rain fall, and the gradual decrease during the following dry period. The maximum of conductivity occurs in July and August. This was rather unexpected, since the wet season is in spring. It seems that the increase of conductivity of the moisture at high summer temperature amounts to more than the increase of moisture during the wet but cooler spring season.

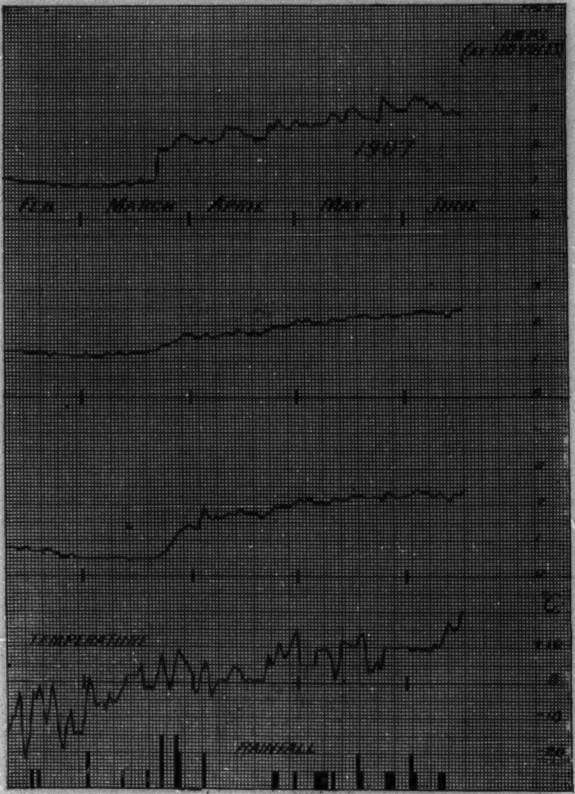

Fig. 3[1]

The minimum of conductivity is towards the end of March. Since thunder storms occasionally occur before this period, this feature requires serious consideration. So far the values of the present year approximately repeat last year's record, except in winter: during the last winter the conductivity decreased to very much lower values than in the previous winter. Whether this was due to the greater severity of the last winter, must remain for further investigation.

Interesting is the great difference between the three grounds although closely adjacent to another. Ground I shows the effect of rain fall and dry periods very much more than II and III. II and III during summer are very closely the same, while I has a considerably higher conductivity, about 30%. From October onward the conductivity goes down, and towards the end of December, II and III, which until then were very closely alike, begin to differ, III decreasing much more rapidly, to a minimum in March, of less than 0.5 amperes or less than one-sixth of the summer value, while II reaches a minimum of 1.15 amperes or about one-third of the summer value, and I, which has been of higher conductivity during summer, falls below II towards the end of January, reaching a minimum of 0.9 amperes. Towards the end of March all three grounds rapidly rise in conductivity, with the spring thaw, in the beginning of April.II and III are again alike, and I of higher conductivity than the other two.

It seems herefrom that such gas-pipe grounds are permanent at least for some years, but show a marked annual variation, the conductivity greatly decreasing during winter. But, against expectations, even at the winter minimum, a very appreciable conductivity is left. The most important conclusion is, however, that such grounds show very great individual difference in their annual variation, even when closely adjacent to each other. This matter requires a further and more extended investigation, which has been started and will be reported upon at a future time.

An interesting and useful feature observed was that by the passage of an alternating current through the pipe into the ground, the conductivity gradually increased, for instance:

Circuit closed at noon:

0	hours	after:	3.40	amperes at 120 volts
7	"	"	3.90	"
9	"	"	4.33	"
22	"	"	4.42	"
43	"	"	4.50	"
52	"	"	4.69	"
75	"	"	4.78	"
103	"	"	4.74	"
120	"	"	4.73	"

Circuit opened at noon:
0 hours after: 4.73 amperes at 120 volts.
7 " " 4.02 "
23 " " 3.62 "

APPENDIX

As the daily measurements of the gas-pipe grounds have been continued during the time which has elapsed since the reading of the above paper, in Fig. 4, the record of Fig. 1 is continued to the middle of February 1908. As seen, the curves in Fig. 4 show the same characteristics and the same values as in Fig. 1:

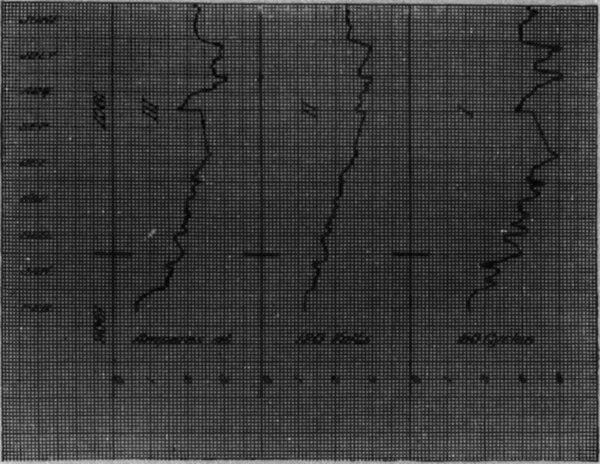

FIG. 4

I gives a higher summer maximum, and a far greater variation of the conductance with the rainfall; II and III are practically alike until the arrival of very cold weather, which this year occurred at the end of January, when III went far down below II in conductance, just as it did in former years.

It seems, herefrom, that at least during the period of observation, of nearly three years, the gas-pipe grounds showed no permanent change, but merely periodic variations with the seasons of the year.

DISCUSSION ON "NOTES ON RESISTANCE OF GAS-PIPE GROUNDS" AT NIAGARA FALLS, N. Y., JUNE 26, 1907

Chas. P. Steinmetz: It seems that the continuous passage of an alternating current through such a gas pipe to the ground increases the conductivity. This test of increase of conductivity was made in the summer time. It stands to reason that during winter the increase will be very much more because of the melting ice. The curves given in the paper show interestingly how towards the winter the conductivity gradually falls and reaches the minimum towards the end of March and then very suddenly jumps up. It also shows many times after a rainfall a sudden rise of current which gradually fades out, and how all three grounds go together until the end of the year and then the one current becomes very small, while the other is still high, and the low resistance ground has reached a higher resistance than one of the high resistance grounds.

This is only a preliminary report, but it is interesting to know that such a gas-pipe ground, which has been called bad names for a long time, seems to remain a ground even in winter when everything is frozen, even if it does not come below the frost line. It is naturally not good enough to discharge a large current, but is good enough to dissipate all electrostatic discharges which may accumulate in the line. It remains to be investigated whether grounds in different places, different soils, etc. may not give still greater values and show different results.

Ralph D. Mershon: Why not extend these investigations to other forms of ground? Why not compare pipes with some of the other forms of ground?

Chas. P. Steinmetz: That is what Mr. Hayden is arranging to do, to start an investigation on a larger scale. There have been a number of suggestions already made, in connection with gas-pipe grounds, of filling the hole up with coke and salt and other materials. It remains to be investigated, whether there is any benefit in digging a hole and filling it with coke, or whether driving a pipe into the ground is not nearly as good. Another question is as to how the character of the surroundings affect the ground, whether to drive the ground pipe in the middle of a road, or to drive it under trees. We are putting down a large number of these gas pipes scattered over the college grounds at Schenectady, and expect to get further results from these tests.

F. B. H. Paine: Do I understand that the gas pipe introduced farthest into the earth has the least resistance?

Chas. P. Steinmetz: The least resistance, or highest conductivity in summer, but in winter it falls in conductivity below the one which was less deep. The shallowest one showed the best conductivity in winter, more than twice the conductivity of the other one, which was a little deeper, and nearly twice the conductivity of the one which was deepest. We measured at lower voltages by putting high resistance in series; instead of 120 volts, 40 or 50 volts gave the same resistance.

P. H. Thomas: If you had 100 amperes it might be different?

Chas. P. Steinmetz: The resistance would probably go down, due to the heating, and so it would show the time effect. Perhaps with high voltages and extremely large currents, but with a range of 120 volts or less the resistance would be constant.

Ralph D. Mershon: We made a somewhat similar investigation. The railway companies were very particular about having our structures grounded near the tracks, and they designed some elaborate grounds, groups of steel rails surrounded with coke. Mr. Nicholson made some measurements on the concrete tower foundations and also the resistance of some of these grounds. First he tried to use a Wheatstone bridge, but the stray currents from different places in the country bothered him. Then he used a modified Wheatstone arrangement in which you make use of the stray current to measure the resistance. He got results which were concordant, but he found that with a voltmeter he could always get a voltage sometimes in one direction and sometimes in the other, between the tower and a pipe driven in the ground. Then he drove two exactly similar pipes in the ground to the same depth, and got a voltage between them. Then he put two pipes in a barrel of water and got a voltage between, and he found he could reverse the voltage by the amount of immersion of the pipe.

F. B. H. Paine: It is my recollection that the same foundation resistances were measured at different times in the year, but certainly during the summer and fall, but I think later on in the winter the variation in resistance was so slight as to be comparatively negligible: it varied between 7 and 10, and 7 and 12 ohms, at different times of the year, the same foundation, not more than that

N. J. Neall: What is the ohmic resistance of the concrete foundations under the tower?

Ralph D. Mershon: The highest is 20 ohms, and the lowest is 3 ohms from the tower to the ground. These values were got by measuring the resistance between the two adjacent towers and assuming that half the resistance was in each one. I think there is room for further investigation in regard to these grounds, not only as to the ohmic resistance, but as to the part they play in case of surges.

Chas. P. Steinmetz: We are going to try to measure not only with 60-cycle current, but also with the high frequency current, 100 000 cycles.

Ralph D. Mershon: I got one railway company to allow me to dig a trench and put in a strip of copper—they finally agreed to let me put in galvanized iron—with some coke around it to make a good contact with the ground.

Chas. P. Steinmetz: Mr. E. J. Berg some years ago proposed to run a shallow ditch along the line and run an underground wire in the ditch and connect that up with the overhead ground wire and use it as an energy dissipating wire, instead of the ground.

Discussion

F. J. Hoxie (by letter): In 1906 and 1907, I made a series of measurements to determine the amount of protection that could be expected from pipe and plate grounds on lighting systems. The paper by Mr. Hayden shows considerably less resistance for the same area of earth contact than is indicated by my measurements. This is probably due to a finer soil and a greater amount of salts dissolved in the ground water, for plates only a few feet apart in different kinds of dirt and in the water of the same pond show large differences in resistance. References to the resistance of ground plates in electrical literature are generally indefinite, but they give the impression that a copper plate of moderate dimensions buried in permanently moist earth will have a resistance of about ten or fifteen ohms. As this is greatly at variance with the facts, in some parts of Rhode Island at least, the following measurements may be of interest.

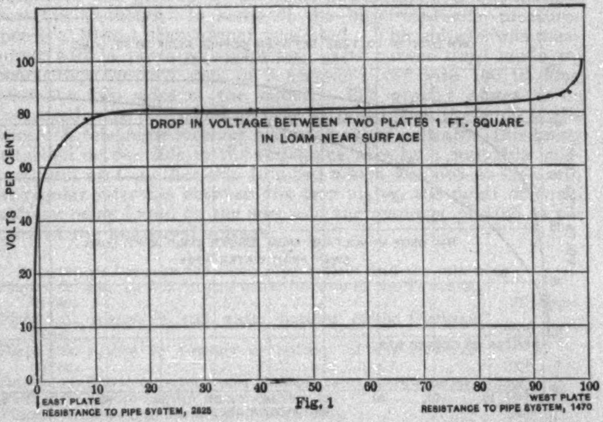

Fig. 1

These measurements were all made in Rhode Island, in a soil very free from soluble minerals. Most of them were made where there is an underlying ledge of granite about 60 ft. below the surface and the ground water level is just above this ledge. Between the ledge and the surface loam the soil is mostly silica, sand, and small stones of varying sizes, unevenly mixed and apparently the result of a violent movement of water in past ages. The well-water contains about 100 parts of mineral matter and the river-water about 30 parts in 1,000,000. The surface loam is of a reddish color, somewhat sandy, and from one to three feet thick.

The resistance of plates or pipes buried in this soil varies so greatly from the figures mentioned above that it is evident that a copper plate of any reasonable size is not a safe ground for a lighting system carrying large currents at moderate potential. By referring to the table of measurements, it will be seen that the resistance of a metal plate one-foot square in the surface loam is about 2000 ohms, in the underlying sand about 11,000 ohms, and in the ground water at the bottom of a well about 300 ohms. Rainy or dry weather makes comparatively little difference to the resistance, except in case of the sand.

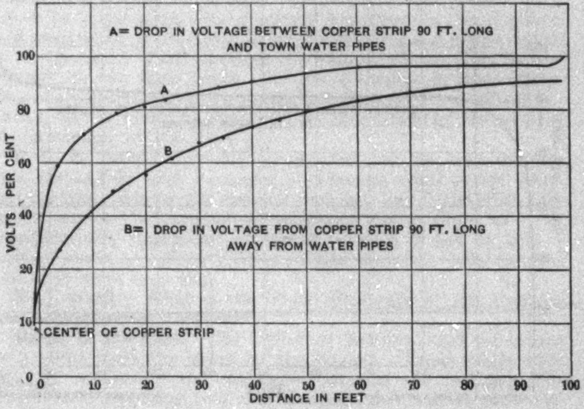

FIG. 2

As the area of a plate is increased, the resistance is not proportionately diminished, but in about the ratio of the square root of the areas; but when a number of small plates widely separated are connected to form a single ground-connection, their separate conductivities are added, as shown by the resistance of 13 ohms of the thirty 1.25-in. pipes driven into the ground five feet at intervals of 300 ft.

The curve in Fig. 1 shows the drop in potential between two plates one-foot square buried near the surface of the ground 100 ft. apart. Fig. 2 is a similar curve of the drop in potential, between a copper ribbon, buried in a straight line 90 ft. long and one foot under the surface of the ground, and a town water-pipe system.

Greater depth does not necessarily decrease the resistance of a ground plate. In this location the reverse is true until the ground water is reached, as is shown by the resistances of plates in the surface loam and in the sand where the loam has been removed. The conductivitiy of ground plates or pipes is apparently governed by the laws of solutions of electrolytes as to variation with temperature and concentration. The coarseness of the soil in contact with the plate also affects the conductivity, as the area of contact is greater with a fine than with a coarse soil, unless the plate is below the ground water level.

The method of measurement used was as follows: the 60-cycle, 104-volt, public service current was grounded on one side to the public water-pipe system, the other side of the circuit was connected to the ground to be measured through a one-ampere portable ammeter. In some of the high-resistance measurements a 10-to-1 transformer was used. The voltage was measured with a portable voltmeter. The curves were made by connecting the two ends of a german-silver wire 100 ft. long with the two sides of the circuit. The ground plates to be measured were connected as near as possible to the ends of the wire. A telephone receiver was used as an indicator, this being attached on one side to the resistance wire by a movable contact, and on the other side to a rod which was put in the earth at regular intervals between the two plates, the point of equal voltage being found on the wire and the readings plotted as per cent. of the impressed voltage.

Resistances between the town pipe system and the following:

Plate 6 ft. 2 in. by 3 ft. in still water bottom of the Pawtuxet river	32	ohms
Plate 1 ft. square in still water bottom of the Pawtuxet river	132	"
Plate 1 ft. square in current in bottom of the Pawtuxet river	232	"
One cu. ft. Pawtuxet river water between two opposite faces	2800	"
Plate 1 ft. square in rain water cistern	197	"
Plate 1 ft. square in stoned well 45 ft. deep	280	"
Plate 1 ft. square in cement cylinder well 50 ft. deep	406	"
One cu. ft. well water between opposite faces	437	"
Plate 1 ft. by 2 ft. on ledge in bottom of Pawtuxet river, rapid current	324	"
Plate 1 ft. square in stoned well 40 ft. deep	310	"
Plate 6 ft. by 2 ft. 3 in. in three bushels coke 6 ft. deep in moist black loam	113	"
1.25 in. gas pipe driven into gravelly ground about five feet	630	"
Nail driven into apple tree about 6 ft. above the ground	3855	"
Wire around and forced into bark of apple tree limb 7 in. in diameter	3030	"
Seven 1.25 in. pipes 5 ft. long and 300 ft. apart in swampy ground	15	"
Ten 1.25 in. pipes 5 ft. long and 300 ft. apart, gravelly ground	53	"
Two 1.25 in. pipes 5 ft. long and 300 ft. apart, gravelly ground	272	"
Thirty 1.25 inch pipes 5 ft. long and 300 ft. apart all kinds of ground	13	"
Plate 1 ft. square in contact with mud on top of frozen ground	3600	"
Plate 1 ft. square in sand, surface soil removed weather dry	11000	"

Plate 1 ft. square in sand, surface soil removed after hard rain	2947	ohms
Average of eight plates 1 ft. square in surface loam.	1940	"
Plate 1 ft. square under shed, ground saturated with brine, soil as above	175	"
Copper ribbon 0.5 in. wide and 90 ft. long buried in surface loam 1 ft. deep and in a straight line.		
June 10, after a heavy rain	107	"
June 23	110	"
October 6	121	"
October 7, after heavy rain	118	"
November 12, morning after heavy rain clearing up	107	"
November 12, noon clear	117	"
November 13, ground slightly frozen on top	122	"
December 2, ground frozen	142	"
March 17, 1907, ground frozen deeply and covered with snow.	155	"
Plate 1 ft. sq. in medium coarse sand bottom of warm cellar.	9600	"
Plate 1 ft. sq. in fine clay-like sand bottom of warm cellar	2160	"
Plate 1 ft. sq. in red sandy loam in bottom of warm cellar	716	"
Plate 1 ft. sq. in sifted red sandy loam under building not heated	1550	"
Plate 1 ft. sq. in highly fertilized garden loam	860	"
Plate 1 ft. sq. in very fine sand in garden under surface loam.	1000	"
Plate 1 ft. sq. in red loam just under the grass roots of orchard	2300	"
120 ft. No. 12 copper wire in straight line about 3 in. under the sod	220	"

Except the river and pipe grounds, the above measurements were all made within a few hundred feet of one another, with the geological conditions practically the same, and are mostly averages of readings made between February 1 and June 1, 1906.

J. L. R. Hayden (by letter): Mr. F. J. Hoxie's tests are very interesting and show what high resistances ordinary copper plate grounds may occasionally give. They hardly represent average conditions, but show rather an abnormally low conductivity of the soil in which they were placed.

Since presenting my paper, a large number of gas pipes, treated in different manners, have been located in different places and are being regularly tested; these show about the same magnitude of resistance, some even a much lower resistance than the grounds recorded in my paper.

It undoubtedly is necessary, when using a gas pipe or copper plate as ground, to test it first, before relying on it, and a very convenient way is to put down two pipes at some distance from each other and test them against each other. Connected in multiple for use, the resultant resistance is one-quarter or less of the sum of their resistances, as given by the test.

A good location for grounding pipes is on a lawn, and it may even be advisable to plant a lawn around the pipes, since the keeping of the grass green by watering insures moisture to maintain the conductivity of the ground, and so gives an indication of their operativeness.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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TRANSMISSION LINE TOWERS AND ECONOMICAL SPANS

BY D. R. SCHOLES

For any given transmission line there is a certain length of span which is most economical. A determination of what the economical span is, in any case, can only be made by obtaining data showing the variation of each item of cost which changes with the length of span. In a steel-tower line the cost of the tower is probably the most important among those items which vary with the length of span. As the span is made longer, the towers must be made higher and stronger. The purpose of this paper is to describe a method by which the relation between the height, strength, and cost of a tower of given form may be expressed. The application of this method to the problem of fixing the economical span will also be shown.

A transmission tower has, in general, three duties to perform:

1. It must have strength to resist wind pressure on its various members.
2. It must have strength to withstand certain external loads due to cables, guys, etc.
3. It must have strength to sustain its own weight.

The weight of a given transmission tower may therefore be considered to be made up of three components, each component corresponding to one of these sources of stress. The following equation may then be written for the weight of the structure shown in diagram in Fig. 1,

$$W = W_W + W_L + W_S \qquad (1)$$

in which W = total weight.
W_W = weight necessary to provide strength against wind pressure.
W_L = weight necessary to provide strength against external loads.
W_S = weight necessary to enable the structure to sustain its own weight.

Assume that the structure shown in Fig. 1 has been designed for a certain wind pressure, and for certain external loads of given amount and manner of application. Each member in the structure may be considered to involve three components of thickness, each component corresponding to one of the three general sources of stress. In determining the value of W_W, the stress in each member resulting from wind pressure alone would first be computed: with this as a basis, the component of thickness of each member necessary to sustain the stress due to wind pressure alone would then be calculated. Having determined the component of thickness of each member corresponding to the stated wind pressure, the value of W_W would follow directly. A similar method would be used in finding W_{SL} and W_S.

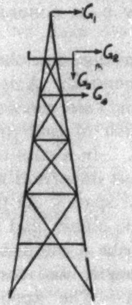

FIG I

This method will, perhaps, be made more clear by referring to Fig. II, which shows in cross-section one of the members of the tower of Fig. I.

In the figure,

t = total thickness.

t_W = thickness corresponding to wind pressure.

t_L = thickness corresponding to external loads.

t_S = thickness corresponding to weight of structure.

t_{SW} = thickness corresponding to component W_W of the weight of the structure.

t_{SL} = thickness corresponding to component W_L of weight of structure.

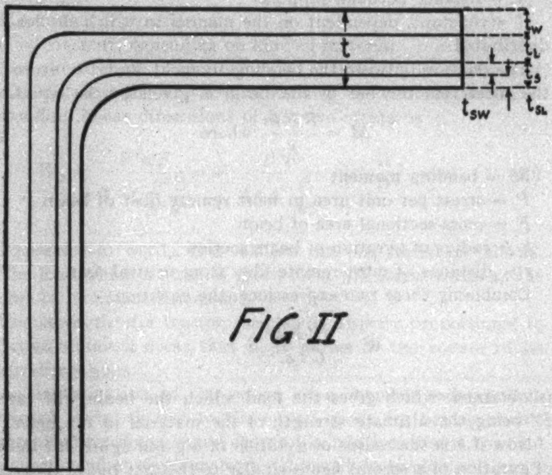

FIG II

$$\text{It is seen that } t = t_W + t_L + t_S \tag{2}$$

$$\text{and, } t = t_W + t_L + t_{SW} + t_{SL} \tag{3}$$

$$\text{since } t = t_{SW} + t_{SL}.$$

The thickness of any other member of the tower may be considered to be divided up into parts in the same manner. Since t_S is divided into the parts t_{SW} and t_{SL}, a corresponding division may be made in the term W_S of equation (1) which gives

$$W = W_W + W_L + W_{SW} + W_{SL} \tag{4}$$

where W_{SW} = weight necessary to provide strength to sustain

W_W and W_{SW}, and W_{SL} = weight necessary to provide strength to sustain W_L and W_{SL}.

The structure shown in diagram in Fig. I involves members of three general kinds; namely, beams, struts, and tension-members.

The bending moment produced in a given beam by a given load W may be expressed by the equation,

$M = CWl$ where (5)
M = maximum bending moment
l = distance between supports
C = constant, dependent on the manner in which the load is distributed.

The relation between the bending moment and the stress in the most remote fiber of the beam is given by the equation,

$$M = \frac{P F k^2}{e} \text{ where} \tag{6}$$

M = bending moment
P = stress per unit area in most remote fiber of beam
F = cross-sectional area of beam
k = radius of gyration of beam section
e = distance of most remote fiber from neutral axis.

Combining these two expressions, the equation

$$W = \frac{P' F k^2}{C l e} \tag{7}$$

is obtained, which gives the load which the beam will carry, P' being the ultimate strength of the material in the beam.

Now if k is the radius of gyration of a given figure, the radius of gyration of a second figure similar to the first but of different size is equal to nk, n being the ratio between corresponding linear dimensions of the two figures.

If, therefore, a second beam be considered, exactly similar to the first but of different size and length, n being the ratio between corresponding linear dimensions of the two beams, the load which this second beam will carry is

$$W_2 = \frac{Pn^2Fn^2k^2}{Cnlne} = n^2 \frac{PFk}{Cle}, \text{ and } \frac{W_2}{W} = n^2 \tag{8}$$

Expressed in words, this relation may be stated as follows: The load which a beam of given form will carry varies as the square of its linear dimensions.

The strength of a strut against compressive stress is given by Rankine's formula:

$$W = \frac{P' F}{1 + C \frac{l^2}{k^2}}, \text{ where} \tag{9}$$

W = ultimate strength of strut
P' = ultimate compressive strength of material
F = cross-sectional area
l = length
k = radius of gyration
C = constant, depending on kind of material.

And the strength of another strut, exactly similar to the first but of different size and length, n being the ratio between corresponding linear dimensions of the two struts, is

$$W_2 = \frac{P' n^2 F}{1 + C \frac{n^2 l^2}{n^2 k^2}} = n^2 \frac{P' F}{1 + C \frac{l^2}{k^2}}, \text{ also } \frac{W_2}{W} = n^2 \tag{10}$$

Expressed in words, this relation may be stated as follows: The load which a strut of given form will carry, varies as the square of its linear dimensions.

The strength of a tension member is directly proportional to its cross-sectional area; that is, it varies as the square of its linear dimensions.

An investigation of the action of a member subjected to torsional loads, similar to those just made for beams, struts, and tension-members, would show a like relation; that is, the load which a member of given form subjected to torsion will carry varies as the square of its linear dimensions. This investigation is not undertaken here, however, because members of this character are little used in transmission towers.

Returning to the structure shown roughly by Fig. I. It is usually assumed that the actual pressure on any part of such a structure, produced by a wind of given velocity, is directly proportional to the exposed area of that part. Now the exposed area of any part is, in general, dependent on its length and breadth, but not upon its thickness. It therefore follows that if the structure shown in Fig. III is geometrically similar to that of Fig. I, in every respect except the thickness of its parts, and is of different size, the ratio between corresponding linear dimensions being n, the load produced on any part of the second structure by a wind of given velocity is equal to n^2 times the load produced on the corresponding part of the first structure by the same wind. It also follows that the stress in any member of the second structure under these conditions, due to wind pressure, is equal to n^2 times that in the corresponding member of the first structure.

For the structure of Fig. III,

$$W' = W'_W + W'_L + W'_{SW} + W'_{SL} \tag{11}$$

and

$$t' = t'_W + t'_L + t'_{SW} + t'_{SL} \tag{12}$$

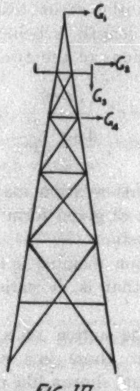

FIG III

From the foregoing discussion of the relation between the size and strength of beams, struts, etc., of given form, it is evident that

$$t'_W = n\, t_W \tag{13}$$

and

$$W'_W = n^2 W_W \tag{14}$$

both structures being calculated for the same wind pressure.

Again referring to the equation for beams,

$$W = \frac{P'Fk^2}{Cle}, \text{ or } F = \frac{WCle}{P'k^2} \tag{15}$$

It is evident that, if k and e can be kept constant, the sectional area which a given beam must have to sustain a load distributed in a given manner varies directly as the load and directly as the length of the beam. The sections commonly employed as beams are angles, channels, and I-sections. By reference to any handbook of such sections, it will be seen that for any of these sections of a given nominal size the area of the beam may vary considerably without producing more than a negligible change in the value of k or e.

Hence, if after the nominal size of a beam has been determined, it is desired to vary either the load or the length of the beam, the sectional area should be made to vary directly as the load and directly as the length of the beam.

From the formula for columns,

$$W = \frac{P'F}{1 + C\,\frac{l^2}{k^2}}, \text{ or } F = \frac{W\left(1 + C\,\frac{l^2}{k^2}\right)}{P'} \qquad (16)$$

it is seen that, if the ratio l/k is kept constant, the strength of the column is directly proportional to its cross-sectional area.

From the nature of a tension-member, its strength is proportional to its sectional area.

Again refer to Fig. I. It is assumed that this structure is subjected to the loads G_1, G_2, G_3, etc., these loads being placed upon it through cables, guys, or the like. The application of each of these loads will, in general, produce certain stresses in each of the members of the structure. The stress in a given member produced by a given load will be directly proportional to the load, and the magnitude of the stress will depend on the particular position which the member occupies. If a certain system of loads, as G_1, G_2, G_3, and G_4, is applied to the structure, the resultant stress in any given part may be considered to be made up of the components $A\,G_1$, $B\,G_2$, $C\,G_3$, and $D\,G_4$; A, B, C, and D being constants. Also, if each of the loads is multiplied by a factor r, the resultant stress in any member will also be multiplied by that factor.

Moreover, if a system of loads, as G_1, G_2, G_3, etc., be similarly applied to another structure geometrically similar to that of Fig. I, but of different size, the stress produced in a given member of the second structure by these loads will be equal to that produced by them in the corresponding member of the first structure. In other words, the stress in any member is dependent only upon the geometrical form of the structure and the amount and manner of application of the loads producing it, and is not affected by the actual size of the structure.

Let the structure indicated in Fig. IV be geometrically similar to that of Fig. I in all respects except the thickness of its members. Let the system of loads, $r\,G_1$, $r\,G_2$, $r\,G_3$, and $r\,G_4$, applied to this structure be similar to that applied to the structure of Fig. I, but of different magnitude, the ratio between corresponding loads being r. Also let the structure of Fig. IV. be designed for a different wind pressure from that of Fig. I. the ratio between the wind pressures per unit area in the two cases being p.

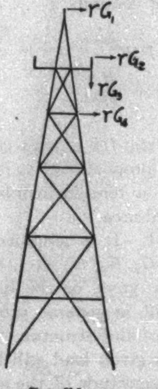

FIG IV

For the structure of Fig. IV,

$$W'' = W''_{W} + W''_{L} + W''_{SW} + W''_{SL} \qquad (17)$$

$$t'' = t''_{W} + t''_{L} + t''_{SW} + t''_{SL} \qquad (18)$$

In view of the relations pointed out between the length, sectional area, and strength of the various kinds of members involved in the structures, it follows that

$$W''_{W} = n^3\,p\,W_{W} \qquad (19)$$

$$W''_{L} = n\,r\,W_{L} \qquad (20)$$

$$W''_{SW} = n^4\, p\, W_{SW} + \ldots \tag{21}$$

$$W''_{SL} = n^2\, r\, W_{SL} + \ldots \tag{22}$$

To make equations (21) and (22) strictly accurate, terms must be added to represent the weight added to provide for the strength necessary to take care of each individual increment of weight. This will involve a convergent infinite series in each case. All terms of these series, except the first, are, however, relatively unimportant and will therefore be neglected.

Substituting in equation (17),

$$W'' = n^3\, p\, W_W + n\, r\, W_L + n^4\, p\, W_{SW} + n^2\, r\, W_{SL} \tag{23}$$

This is a general equation, and, given the values of W_W, W_L W_{SW}, and W_{SL} for the structure of Fig. I, it makes it possible to calculate the weight of the structure of Fig. IV. without going through the routine of calculating the stresses in each member and the sizes and weights of the parts necessary to carry these stresses.

The application of this formula to the problem of fixing the economical span for a given transmission line is obvious. A tower for a given length of span would be designed to furnish the strengths necessary for that span. The design would be made in accordance with the manufacturing facilities available for producing the structures. The stresses in each member would be carefully calculated and the values of W_W, W_L, W_{SW}, and W_{SL} found for the structure. Having found these values, the weight of any similar structure for any length of span could be determined by substitution in equation (23).

It is to be observed that this method of treating the case assumes that both wind loads and external loads are to be applied to the structure simultaneously. This is usually the case. In other cases, however, the method to be pursued would be similar, but modified to suit the peculiarities of the case.

It is also to be borne in mind that formula (23) contemplates that variations in the cross-section of any member will be made in such manner that the radius of gyration of the section will be kept proportional to n in every case, and also that no appreciable variation from geometric similarity will occur. These assumptions do not involve any appreciable inaccuracy within the range of ordinary practice.

Before the problem of providing steel towers for supporting the cables of a given transmission line can be considered, the general features of the line, its voltage, size of conductor, etc., must be fixed. To show the application of the formula just developed, the following set of general assumptions has been selected as a working basis, and it is believed that they are in accord with average high-grade practice.

GENERAL ASSUMPTIONS

System: three-phase alternating current.

Conductor: 400,000 cir. mils stranded copper. Cross-sectional area 0.3145 sq. in. Outside diameter 0.73 in. Weight per foot 1.22 lb.

Spacing: 7 ft. delta, for 500-ft. span.

Minimum clearance: 30 ft. between ground and lowest conductor at center of span.

Temperature range: 40° fahr. to 110° fahr.

Sleet: 0.5 in. all around cables. Diameter of conductor with sleet 1.73 in. Weight per foot with sleet 1.98 lb.

Wind pressure: 30 lb. per square foot normal to plane surfaces.

Test factor of safety: 2.

It is further assumed that, at occasional intervals along the line, the structures will be stayed by guy-cables in the direction of the line, and that the cost of such staying will not vary with the length of span. To provide in all structures a certain amount of strength against loads on the insulators in the direction of the line, it is assumed that in the tower for the 500-ft. span an unbalanced test load of 2000 lb. will be applied to the top of each insulator pin in a horizontal direction parallel to the line.

In explanation of the term "test factor of safety," it may be said that it has become usual for purchasers, in issuing specifications for towers, to require that the structures must show, under actual test, their ability to withstand the loads due to the assumed wind pressures, weights, etc., with a certain factor of safety. In calculating the load to be applied to the top of an insulator pin, for instance, to test it for strength against wind pressure on cables, the effective area of the cable with sleet would be multiplied by the stated wind pressure and by the factor 2. The load thus obtained would then be actually applied to the structure, and its acceptance would depend upon its ability to withstand such tests. In order that the structure may have a certain margin of strength over and above that actually required to withstand tests based on a test factor of safety of 2, the sizes of the members will be calculated with reference to a factor of safety of 2.5 based on ultimate strength.

In determining the sag corresponding to each length of span, reference has been had to the curves given in Fig. 9, calculated by Mr. Ralph D. Mershon, and here reproduced through his courtesy. These curves indicate in each case the sag for maximum temperature, this sag being so determined that, when under minimum temperature and maximum wind and sleet loads, the conductor will not be stressed beyond its elastic limit.

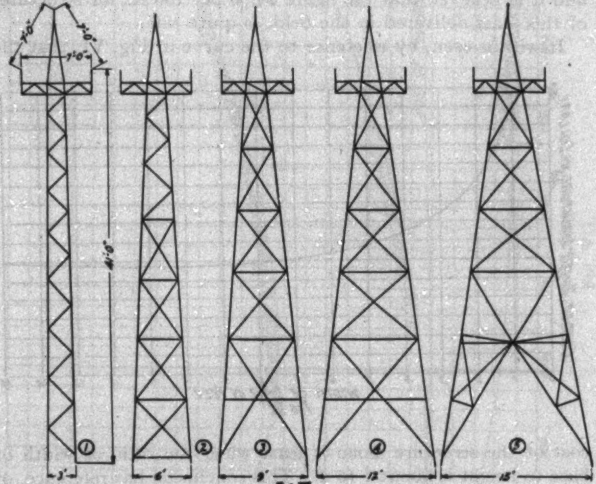

FIG. V

With the foregoing set of conditions at hand, computations have been made of the cost of each of a series of structures for a 500-ft. span these structures being of varying width of base but uniform in height. The purpose of these computations is to show the relation between the width of base and cost for such structures, and to obtain an indication as to what ratio between height and width of base is most economical. This series of structures is shown in diagram in Fig. V. A curve is given in Fig. VI showing the relation between the width of base and the cost per structure. The cost of each structure has been figured on a basis of $4.50 per 100 lb. delivered in the field. The construction involves standard angle and flat steel sections, standard butt-weld pipe, and some simple forgings. It has been assumed that all parts would be properly galvanized, so no limitation has been made as to the minimum thickness of material, it being simply required that the members be of sufficient strength to meet the conditions laid down. The construction admits of shipment knocked down and bundled, and it is believed that the figure $4.50 per 100 lb. for structures of this class delivered in the field, is quite safe.

It will be seen, by reference to the curve in Fig. VI, that the cost of the structure alone is least when the ratio of width of base to height is about 1 to 4. This conclusion has reference, of course, only to the span of 500 ft. and to the conditions and type of construction adopted.

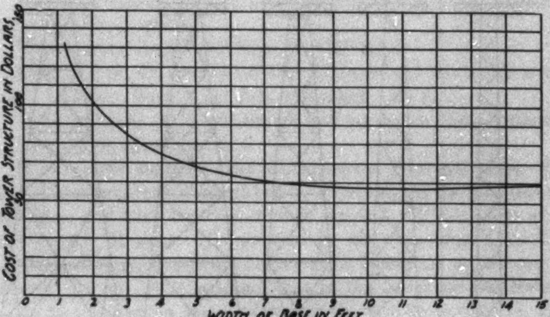

FIG VI

The width of base of the structure has an important bearing on the cost of the line, aside from its effect on the cost of the tower structure itself, since it affects the cost of foundations, the cost of right of way, and the cost of assembling and raising the structure in the field. Now it is a difficult and uncertain matter to estimate the variation of cost of these items for a general case. Hence a determination of the economical width of base for certain assumed conditions would be of but little interest in the present connection.

APPLICATION OF THE FORMULA

The structure having a width of base equal to one-fourth its height has been selected as a basis for calculations of the weights of towers for longer spans. An investigation of this structure has been made to determine the values of W_W, W_L, W_{SW}, and W_{SL}, and the following values arrived at:

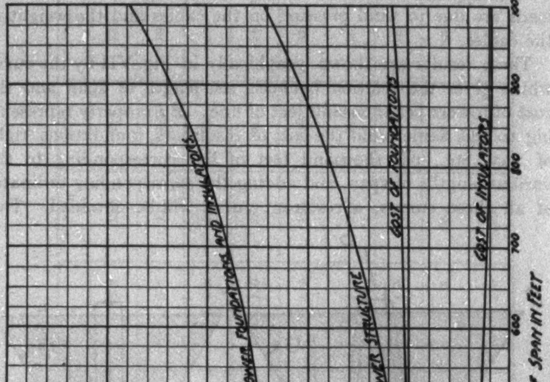

FIG. VII.

$$W_W = 383 \qquad W_{SW} = 34$$
$$W_L = 813 \qquad W_{SL} = 60$$

The table given later shows the results obtained by means of the formula for a series of towers similar to No. 4 in Fig. 5, but for spans up to 1000 ft. Since all towers in the series are to be for the same wind pressure, p is equal to unity in each case. Also, r is proportional to the length of span, since the external loads are due to wind pressure on the cables and the weight of the cables.

These results are shown graphically in Fig. VII by the curve which gives the relation between the length of span and the cost of towers per thousand feet of line. By properly representing to this same scale the cost of insulators, foundations, right of way, etc., per thousand feet of line corresponding to the various lengths of span, and adding the corresponding ordinates of all these curves, a resultant curve will be obtained. This resultant curve will show the relation between the length of span and cost of those items which vary with the length of span, and it will therefore indicate the economical span for the assumed conditions.

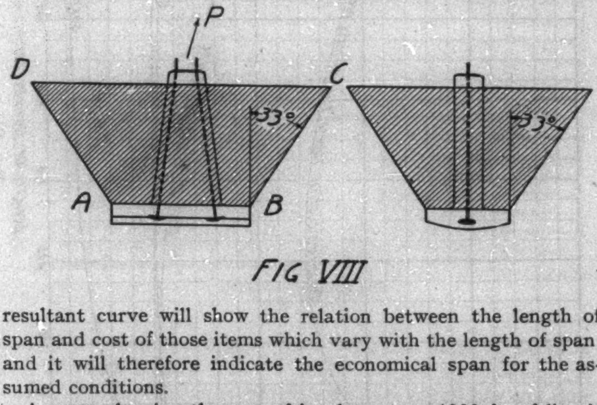

FIG VIII

A curve showing the cost of insulators per 1000 ft. of line is given in Fig. VII, the insulators having been figured at $5.00 each, erected in the tower and with the conductor secured to them.

The curve in Fig. VII showing the cost of foundations per 1000 ft. of line has reference to the type of foundation shown in Fig. VIII, and to the following method of calculation.

It is a usual assumption that the strength of a foundation against a force tending to pull it out of the ground is directly proportional to the weight of the foundation plus the weight of earth contained in the figure *A B C D*.

If the foundation in Fig. VIII has strength to resist a resultant force *P*, a second foundation, exactly similar to it but of

TABLE 1.

Span	Sag	Height	n	n^2	n^3	n^4	p	r	$n^3 p w_W$	$n r w_L$	$n^4 p w_{SW}$	$n^2 r w_{SL}$	w''
200	2.0	32.0	0.780	0.608	0.475	0.370	1	0.4	182	254	13	15	464
300	4.5	34.5	0.832	0.692	0.576	0.479	1	0.6	221	406	16	25	668
400	7.5	37.5	0.915	0.837	0.766	0.701	1	0.8	294	596	24	40	954
500	11.0	41.0	1.00	1.00	1.00	1.00	1	1.0	383	813	34	60	1290
600	15.5	45.5	1.11	1.23	1.37	1.51	1	1.2	523	1082	52	89	1746
700	20.5	50.5	1.23	1.51	1.86	2.28	1	1.4	703	1405	78	128	2314
800	26.0	56.0	1.366	1.86	2.55	3.46	1	1.6	978	1778	118	179	3053
900	33.0	63.0	1.537	2.36	3.62	5.57	1	1.8	1386	2250	190	255	4081
1000	40.5	70.5	1.72	2.96	5.09	8.76	1	2.0	1950	2800	298	356	5404

different size, would have strength to resist the force $n^3 p$, n being the ratio between corresponding linear dimensions of the two foundations. Now it seems fair to assume that the cost of such a foundation would vary directly as its volume. The cost of the foundation would therefore vary directly as the resultant force which it is capable of resisting.

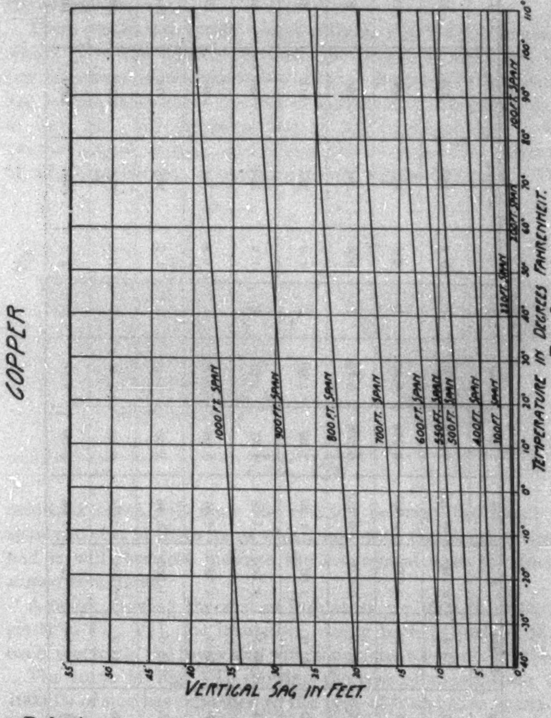

FIG. 9.

Referring to some experiments made at Chicago on a foundation similar to that of Fig. VIII, and to the records showing the actual cost of the foundation in the field ready to receive the structure, the following basis for calculation was obtained:

Resultant force sustained by foundation.....	24,000 lb.
Cost of foundation.........................	$15.25

By calculating the resultant force which would come upon the foundation from each of the structures given in Table I, and making the cost of foundation for each structure proportional to that force, on the basis of the data above given, the curve showing the foundation cost per 1000 ft. of line given in Fig. VII was obtained. It is to be observed that this curve is quite flat, indicating that the foundation cost does not vary to any great extent as the length of the span is varied.

The curve of combined cost of towers, foundations, and insulators was obtained by adding the respective ordinates of the curves giving the separate costs of these items. This curve indicates that, for the assumed conditions, a span of about 425 ft. would be most economical.

It is to be observed that in the foregoing solution the determining factors are the tower cost and the insulator cost. If the price per insulator is increased, the economical length of span would be increased, and vice versa, in other words, the higher the voltage the longer the span should be.

For a low-voltage line the economical span would be somewhere between 300 and 400 ft., as far as the methods of calculation here employed can determine. Each structure in this case would, however, be a very light affair. It is probable, that, in the average case, a somewhat longer span would be decided upon in order to give each structure greater individual strength and thus make it safer against damage due to external causes.

In case it is desirable to impose limitations of this sort, the formula must be modified accordingly, by subdividing the component of weight into parts; as, for instance, by letting

$$W_L = W_{G1} + W_{G2} + W_{G3} + W_{G4}$$

where W_{G1}, W_{G2}, W_{G3} and W_{G4} are components of weight corresponding to the loads G_1, G_2, G_3 and G_4 respectively.

These loads may then be made to vary at different rates, or some may be kept constant and the others varied in such manner as may be desired. Suppose, for example, it is assumed that each structure should have strength to resist the loads due to the breakage of any two conductors. These loads would be the same regardless of the length of span, whereas the loads due to wind pressure on the cables would vary according to the length of span.

These assumptions will, in general, tend to make the economical span longer.

[illegible]

By calculating the [illegible] would correspond the [illegible] loads [illegible] as given in Table 1, [illegible]

[illegible]

It is to be observed that [illegible] the determination [illegible] and the insulator cost. If the [illegible] the theoretical length of span [illegible] In other words, the higher [illegible] the longer the span should be.

From this [illegible] the economical span would be some-[illegible] methods of calcula-[illegible] Each structure in this case [illegible] It is probable that it [illegible] the longer span would be [illegible] again [illegible] individual strength and this [illegible] due to external causes.

In order to [illegible] the formula [illegible] by substituting the component of weight into parts as for instance by letting

$$W_1 = W_{G_1} + W_{G_2} + W_{G_3} + W_{G_4}$$

where W_{G_1}, W_{G_2}, W_{G_3} and W_{G_4} are components of weight corresponding to the loads G_1, G_2, G_3 and G_4 respectively.

These loads may then be made to vary at different rates or some may be kept constant and the others varied in such manner as may be required. Suppose for example it is assumed that each structure should be designed to resist the loads due to the breakage of any two conductors. These loads would be the same regardless of the length of span whereas the loads due to wind pressure on the cables would vary according to the length of span.

This assumption will in general tend to make the economical span longer.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907

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LIGHTNING-RODS AND GROUNDED CABLES AS A MEANS OF PROTECTING TRANSMISSION LINES AGAINST LIGHTNING

BY NORMAN ROWE

The following is practically a summary of lightning trouble during the years 1904, 1905, and 1906, on a steel-tower long-span transmission line in the states of Michoacán and Guanajuato, Mexico.

The main transmission line, built in 1903, was the first one constructed on steel towers. These towers were of standard type, the height being 40 ft. from the top of the cross-arm to the ground. Three wires were placed upon the towers in the form of an equilateral triangle, the upper wire being supported upon a 3-in. extra heavy pipe, which formed the continuation of the tower, the other two being placed at the ends of a double channel-iron cross-arm, approximately 7 ft. in length, the sides of the triangle being 6 ft. The insulators used were 12 in. high and 14 in. in diameter. These insulators were cemented directly on cast-iron pins. The pins for the top insulators were made to screw on the 3-in. pipe; those for the side insulators had a square shank and were secured to the cross-arm by two ⅝-in. bolts. The conductors were 19-strand, hard-drawn copper cable, equivalent to No. 1 B. &. S. solid copper wire. There were no wooden pins or cross-arms used on the towers. For protection against the line voltage as well as any high voltages due to lightning discharges, dependence was placed entirely on the insulators.

The ordinary length of span was 440 ft., but there were several spans of 1200 ft. and one of approximately 1600 ft. The line was designed for 60,000 volts at the generating end and

51,000 at the receiving end. The length of the line was approximately 101 miles.

The line is tapped at Irapuato, approximately 75 miles from the generating station and 26 miles from Guanajuato. At this point there is a sub-station where lightning-arresters of the usual station type are installed to protect the step-down transformers. From this it will be seen that there is a chance for the line to discharge at this point as well as over the arresters at either end of the transmission line.

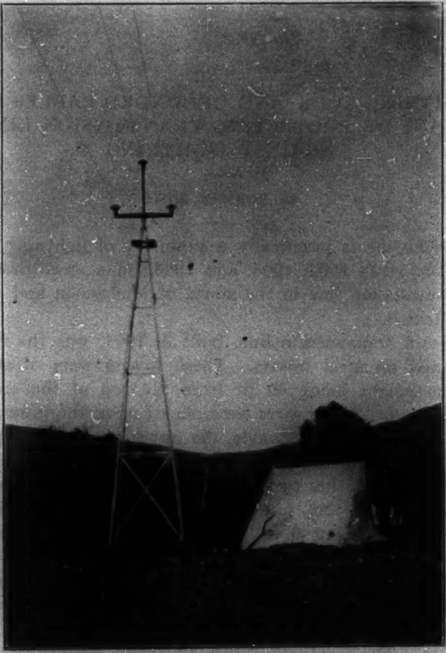

FIG. 1—Showing line as originally constructed

Thus far there have been three rainy seasons, which, in the part of Mexico where the line is situated, generally last from

June until October. Heavy thunder storms come up nearly every day during July and August, and there is a storm on an average of every two days through a period of four months. During the rainy season of 1904, there was considerable trouble with lightning; the next season there was less, and during the rainy season of 1906 comparatively little trouble was experienced. The nature of the troubles, the expedients tried to overcome them, and the provisions for overcoming future lightning troubles will now be considered.

The rainy season of 1904 came on with great severity in April, two months earlier than usual, and lasted until October. The injury to the transmission line from lightning was mostly confined to the puncturing of the top insulators by direct bolts of lightning, and in most cases a hole was bored through the top insulator nearly in a vertical line to the pin. These holes were approximately one inch in diameter and the sides were glazed. Usually, the insulators were badly shattered, but on putting the parts together one could generally find the glazed hole above referred to. Some side insulators were lost, but they were almost invariably injured at the time when the top insulators on the same or adjacent towers were injured. The side insulators were never punctured from the top in a vertical direction, but in some cases they showed a small puncture in a horizontal direction from the tie-wire to the pin. In nine cases out of ten, however, they were not punctured at all, but half of the top and portions of one or both petticoats on the same side were broken, presumably by the power current following lightning discharges over their surfaces.

As the principal trouble apparently came from direct bolts of lightning striking the top insulators, it was thought advisable to erect lightning-rods on the towers on the section of the line where most trouble had occurred. At that time the placing of a grounded cable over the transmission wires was discussed, but as this could not be done before the end of the rainy season, for suitable material could not be obtained in Mexico, it was decided to put up lightning-rods and get the benefit of experience with them during the rainy season then in progress.

Lightning-rods were erected in pairs, starting from the 3-in. pipe at the point where the cross-arm in pairs was attached, and projecting up on either side of this pipe to a distance of 6 ft. above the top insulator at an angle of about 30 degrees from the vertical.

By the middle of August one-half of the line giving the most trouble was equipped with lightning-rods, and there had been erected quite a few rods on towers that were considered as being particularly exposed to danger from lightning. After the erection of these rods the difficulties were very much less, although there was still some trouble on the section of the line where they were in place. In no case were top insulators punctured through from the top as on the towers where rods

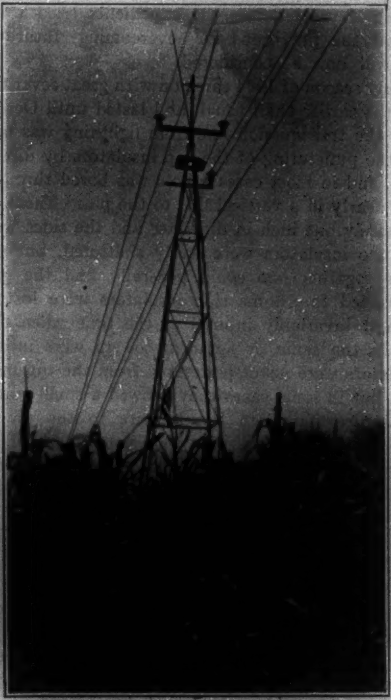

FIG. 2—Showing first change. Top insulator lowered, grounded cable in place, and lightning-rods left in position

were not in place, but when insulators were injured they usually had a part of the top and a petticoat broken on the same side. There were also a few cases where insulators were punctured in a horizontal direction from the tie-wire to the pin. During one very severe storm, eight insulators were broken on seven towers spread out over a distance of 14 towers. As the towers were spaced 12 to the mile it is improbable that the same discharge of lightning could have caused all of this trouble, unless it was transmitted over the power lines. Of the eight insulators injured none was punctured; they were apparently damaged by the current going over their side. Although these insulators were badly injured, the service on them was continued, but at a slightly reduced voltage.

One quite remarkable case happened in the Guanajuato sub-station, due, perhaps, to a bolt of lightning striking the line about a mile away. One of the men was standing in a balcony in Guanajuato watching the lightning display, when apparently a very heavy discharge struck the tower line, located over a hill just out of sight. At the same moment the lights in the room went out, showing that the service had been interrupted. The lightning which caused this interruption of service came into the sub-station over the top wire and jumped 4.5 ft. through air to ground, at the same time going to ground over the lightning-arresters. An insulator over which the arc formed in the sub-station had half of the top cracked off, but no injury was done to the transformers or other equipment. The towers were carefully examined near where the lightning was seen to fall, but there were no broken insulators or other evidence to show that the bolt had struck the line. However, as lightning had been previously seen to strike the towers without causing trouble, it was thought that a bolt of lightning had struck the tower line, a portion of this discharge coming over the wires into the sub-station. At the place where the bolt was supposed to have struck, the towers, on exposed places, were equipped with lightning-rods.

These cases are cited to show that insulators at a distance from heavy discharges of lightning may be subjected to very severe voltages, and, from all the data at hand, it is believed that the lightning-rods were efficient in protecting the insulators from direct bolts of lightning, and that the trouble that was still present on the section of the line equipped with lightning-rods was due to discharges traveling along the transmission wires.

During the season of 1904, the line troubles were quite evenly distributed over the first 50 miles of line out of the generating station. There were only two cases of trouble outside of this section that caused injury to the line insulators. Equipping this section with lightning-rods was begun in June and finished in August. This section of the line, except for a stretch of 15 miles, was left as equipped in August, 1904, until October, 1906, or through more than two lightning seasons. As there was less trouble on this section of the line during these two seasons than during a portion of the lightning season of 1904, it is evident that the lightning-rods were at least partly effective.

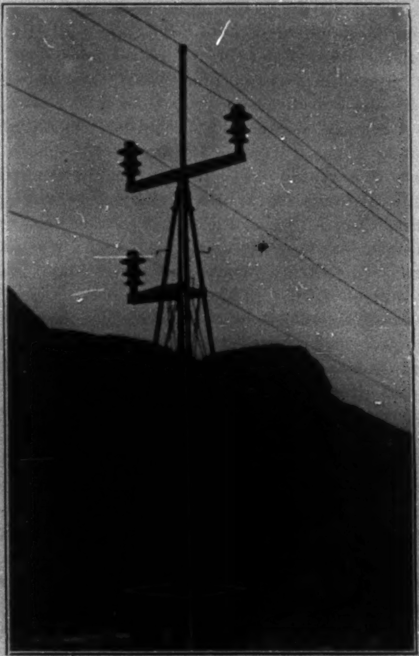

FIG. 3—Showing present appearance of line. Lightning-rods removed.

After finding that lightning-rods were not a complete protection, it was decided to make the experiment of lowering the top wire and putting up a grounded cable in its place. However, on account of delay in receiving material, very little was accomplished in time for the rainy season of 1905 and the experience with lightning during that season was the same as that obtained during the rainy season of the previous year, except that there was much less trouble.

In the winter of 1905-1906, it was decided to install larger insulators on the tower line and at the same time to lower all of the top cable to a position below one of the original side insulators. On the highest point of the tower, in place of the top transmission cable, it was decided to string over the entire line a ¼-in. 7-strand steel cable, grounded at each tower. Insulators 17½ in. in diameter, 20 in. high, were adopted for the first 60 miles of line out of the generating station, and the same insulator with a 14-in. top for the other 40 miles of line. It was unfortunate that the insulators with the 17½-in. top were not ready so as to complete the line changes in time for the rains, but half of the line out of the Guanajuato sub-station was finished before the time for severe lightning storms had arrived. The other half of the line had been equipped the first year with lightning-rods, which were still in place, the top cable being in its original position on this section, except for a distance of 15 miles.

During the rainy season of 1906, the transformers were connected in star on the high-tension side, the center of the star being grounded, and in order to detect instantly when there was a ground on the line, a series transformer was put into this grounded line and the secondary leads carried to the switchboard, where an ammeter was connected to them. With this arrangement, when an insulator broke down, or the power current followed the lightning over the insulator, the station operator could tell when there was a ground on the line, and, by shutting down at once, he was able to prevent the burning off of the transmission wire. Usually, when a ground appeared and the power was cut off, the line was found in good condition on again starting up.

There was no apparent trouble from lightning during the rainy season of 1906 on the section where the grounded cable was in place. On several occasions grounds came on the lines during lightning storms, and the power was immediately cut off in order to clear them. In general, these grounds could not be located, so it cannot be said that lightning did not go over the surface of the insulators on the section where the grounded cable was in place. The section where there was no grounded cable in place, but where the lightning-rods were erected, still gave some trouble, but the total amount was much less than in any preceding year.

The part of the line found to be the hardest to protect during all three rainy seasons was the middle of the 75-mile section

FIG. 4—Insulator perforated and broken by lightning bol

from the generating station to Irapuato; in other words, the part of the line farthest from the location of lightning-arresters. This would indicate that arresters for discharging the line, located say every 25 miles, would be a valuable protection.

The experience of the last three seasons prompts the writer to offer the following suggestions:

1. Insulators should not be disposed upon poles or towers so that they will be in the path of bolts of lightning going to ground by the supporting structure.

2. A grounded cable, strung above the transmission wires at the highest point of the tower, is certainly more effective than lightning-rods in protecting the insulators and conductors from direct bolts of lightning.

3. Lightning-arresters, for discharging the line in case very high voltages are present on the wires, would be of some value if located along the line at frequent intervals.

4. On steel construction, an insulator should be used that has a high margin of safety against puncture and arcing over.

It seems at present general practice to use insulators for high potentials with practically no margin of safety, and when the conditions are severe there is almost sure to be trouble. Aside from trouble with the puncturing of line insulators by direct bolts of lightning, which was apparently prevented by the use of lightning-rods on towers, nearly, if not quite all, of the trouble on this line has come from the breaking down of insulators by the current going over their sides, or through them, from tie-wire to pin. The writer ventures to assert that, if the insulators had been much better, there would have been little trouble on the line where the lightning-rods were in place. Moreover, as a grounded cable undoubtedly affords better protection than lightning-rods, with a suitable grounded cable strung over the transmission wires, and better insulators so disposed as to be out of the path of direct bolts of lightning, even without the installation of lightning-arresters along the line there would result a line that should be practically free from lightning troubles.

NOTE.—While personal experience suggests that the use, on iron construction, of insulators with a high factor of safety will greatly reduce troubles from lightning, it was decided to change our line insulators on account of trouble from an entirely different cause. During some months of the year the insulators become covered with condensed moisture just at sunrise, due to a very sudden rise in temperature, from the temperature of about zero centigrade. This often left insulators, on the portion of the line where the temperature variation was most severe, covered with condensed moisture nearly as heavy as hoar-frost, and, during the few moments when this effect lasted, the power current was apt to arc over the surfaces of the insulators. The old insulators were considered by the company's engineers as the best obtainable in 1902, and the insulators decided upon in January, 1906, were the largest commercial insulators on the market. A very much better insulator was desired, but for want of time to develop something better it was necessary to adopt an insulator with a factor of safety somewhat lower than that intended to be used. The apparent freedom from lightning trouble on the part of the line equipped with larger insulators and grounded conductor is due perhaps as much to the use of better insulators as to the grounded cable.

DISCUSSION ON "TRANSMISSION LINE TOWERS AND ECONOMICAL SPANS" AND "LIGHTNING-RODS AND GROUNDED CABLES AS A MEANS OF PROTECTING TRANSMISSION LINES AGAINST LIGHTNING," AT NIAGARA FALLS, N. Y., JUNE 26, 1907.

William Hoopes: The method of treatment of this problem appears so excellent that one is at once interested in its practical application. The first conclusion reached is that the economical span-length is determined, not by the original cost of the line, but by its annual cost.

The annual cost is made up of three items:

1. Interest and depreciation on the first cost.
2. The cost of repairs and patroling.
3. The money damage from interruptions to the service.

If lengthening the span will reduce the number of interruptions and cost of repairs, then the economical span is longer than that which gives the lowest first cost.

Inquiry into the operation of a large number of transmission lines reveals the fact that by far the larger portion of the interruptions of service is due to trouble occurring at the point of support; this applies particularly to steel-tower lines. Reduction of the number of supports does, therefore, reduce the annual cost.

The paper shows that this particular line on 800-ft. spans would cost about $300 more per mile than if on 400-ft. spans. Interest and depreciation on this at 10% would be $30 per year. Halving the number of supports would probably save much more than this.

I believe the subject has not been treated in this way in this or any other paper, so I should like to suggest to the committee that such a paper would open up a very live topic.

However, the province of Mr. Scholes' paper is really to show the least first cost of the line, and the above remarks are not strictly germane to it. Investigation of its practical application leads to the following queries:

1. Is the assumption of a uniform price per pound justifiable?
2. Does the retention of the same geometrical figure permit the design of all the towers for the least cost?
3. It is fair to assume that large foundations for higher towers cost as much per cubic yard as small foundations for low towers.

The cost of a tower to the purchaser is made up of the following items:

1. Cost of steel and transportation.
2. Cost of shop work.
3. Cost of galvanizing.
4. Cost of erection.
5. Manufacturer's profit.

If the cost of the tower is directly proportional to the weight of the steel, then all of the items of cost must vary at the same rate as the weight. The cost of the steel does vary approximately as the weight.

The paper gives the cost of a 34.5-ft. tower as $30, and of a 70.5-ft. tower as $243, which is about proportional to the cubes of the heights. The other costs should therefore be as the cubes of the heights.

Inquiry from a concern which makes a very large number of towers elicited the following opinions:

1. As the number of parts is the same for large as for small towers, the number of shop operations will be about the same; but as the shop operations will be slower on the heavier work, the shop cost will vary about as the height of the tower.

2. The same opinion was expressed with regard to the cost of erection.

3. The galvavanizing cost is approximately proportional to the superficial area, or to the square of the height. The galvanizing was said to be a very material portion of the whole cost.

When it came to a question of manufacturer's profit the source of my information ran dry, but if it increases as the cube of the height, it would seem to afford a considerable opportunity to a resourceful purchasing agent.

From the foregoing it would seem that all the costs which go to make up the cost of the tower, other than the cost of steel, vary at a less rate than the cost of the steel, and that a smaller price per pound should be used in determining the cost of the large towers than is used for the small towers.

It would add to the value of Mr. Scholes' paper if he would answer my three questions, and I should like to ask further if it is actually possible to furnish a 34.5-ft. tower galvanized, for $30? or a 32-ft. tower for $21? the prices given in the paper.

P. H. Thomas: Mr. Rowe has given us valuable data on the effectiveness of the overhead ground-wire for protecting high transmission lines. The only thing that remains is to draw correct inferences from the data, and that is very difficult to do. There are some salient points, however, which seem to indicate the real lesson of the paper.

In the first place, in judging of the performance of a new line, the necessary elimination of weak insulators which occurs during the early operation must be taken into account. Mr. Rowe says that by the use of a series transformer in the ground connection he has discovered a way to get the current off the line quickly enough not to break the insulators, so that the power could be thrown directly back again. This is an important point to consider, for if that is the way the improved operation was brought about it is no credit to the overhead grounded conductor.

Mr. Rowe says further:

> On several occasions grounds came on the lines during lightning storms and the power was immediately cut off in order to clear them. In general, these grounds could not be located, so it cannot be said that

lightning did not go over the surface of the insulators on the section where the grounded cable was in place.

This apparently indicates that, only improvement resulted from the grounded wire.

Furthermore, in addition to the installation of the grounded cable, there was a change in the size of the insulators, largely on that part of the line protected by the overhead cable. This, in itself, is the very best sort of lightning protection. As Mr. Rowe himself intimates that the original insulators were really too small for their work, it will not be safe to infer too much from the increased satisfaction in the operation after the introduction of the grounded overhead conductors. On the other hand, it is probably certain that the overhead grounded conductor does relieve the line insulation a great deal; especially in the way of reducing the severity of the heaviest strains.

Is it not true that too great a risk is being taken in using steel poles, steel cross-arms and pins, relying wholly on the insulator? It is relatively easy for a charge to pass over the insulator's surface to ground at the pin, and it is usually destructive when it does come, starting an arc to ground which breaks the insulator and tends to shut down the plant. Is there not some way to preserve the advantage of the old wooden pin and cross-arm, which prevented many discharges to ground from becoming short-circuits?

W. S. Lee: As Mr. Hoopes has suggested, we should not try to get too economical a tower or too economical a span. In some cases these transmission lines are carried over a rolling country; in other cases over a flat country with no fall for a water power, so we have to span from hill to hill, and from point to point, and the practical erection of the line means irregular spans. We have found that in our service. Now, while one may figure on a fixed-span tower, the chances are that the spans will be regulated by the topographical conditions. The usual practice is to make a profile of the country. If there is to be a tower for a 400-ft. span, and the next span has to be extended to 550 feet or 650 feet, we would need towers of different strength. It would be best to keep the tower standard on the line, in case of repairs, or shipments of parts; and for that reason I would suggest getting stronger towers which could be used for either long or short spans.

Referring to Mr. Rowe's paper: In 1897 I was with the Anderson Water Light & Power Co., Anderson, S. C., and we built an 11,000-volt line for a distance of 10 miles. While the poles were being constructed, and before there was a wire strung on them, two poles at different points were shattered entirely by lightning. The plant was built and has been in operation since that time; it has two lines of barbed wire overhead. Though there has been some trouble with lightning, they have not had a direct stroke of lightning on that line since that time. The Catawba Power Company, of Charlotte, N. C., has a transmission system of 18 miles. When the line was built in

1904 one pole was struck by lightning, but there was no wire on it. There is one grounded wire overhead, and no pole has been damaged by lightning since that time, nor has there been a direct bolt of lightning.

We built in 1905 at this same station, a line 20 miles long. It had 11,000-volt service, built with 40,000-volt insulators. This was a three-phase, single-circuit line, and in order to arrange for equilateral triangle construction one wire was placed on top of the pole. We endeavored to locate a grounded wire above the apex wire, by extending supports up to this point, and curving them so as to keep away from the apex wire. This arrangement did not work. We found that irregularities in the country resulted in a tendency to pull up or down, in some cases to bring the grounded wire close to the apex power-wire. For this reason the grounded wire was left off this circuit. Since 1904, there have been two direct strokes of lightning on this particular circuit; neither stroke interrupted the service, but both damaged poles by splitting them. All the lines are now being equipped with the overhead grounded wire.

F. B. H. Paine: Mr. Thomas suggested a question which is frequently asked, in view of our extended use of steel poles and towers; whether we are not putting too much trust in the insulator, and would we not do better with the added insulation of pole, cross-arm, and pin? For a good while I was in doubt about it, but after an experience of two years I think that Mr. Mershon's judgment has been amply sustained. I have recently visited many transmission plants, and in every instance I found that the annual destruction of poles and cross-arms, that is, the entire destruction of the supporting structure, exceeded our loss of insulators per mile. We can replace the insulators much quicker and cheaper than we can the entire supporting structure, whether it be of wood, steel, or what-not. We have something like 200 miles of 60,000-volt transmission lines on wooden structures using the same insulators cemented on steel pins, the steel pins being carefully grounded. We have had some terrific lightning disturbances in that section, and, although many insulators have been lost, in no instance has any injury come to the wooden structure on account of the pins being grounded, and to all intents the same condition existed as on the steel tower or steel pole. I think we have answered the question as to the desirability of wood as an insulator for high-voltage lines very effectively: use metal pins, ground them, and save the pole and cross-arm.

C. W. Ricker: The experience of a railway transmission line in western Ohio may be of interest.

This consists of about 100 miles of three-phase, 3300-volt line built in 1901 on wooden poles with wooden cross-arms and porcelain insulators designed for use at that voltage by one of the largest American makers. Each cross-arm had two steel braces applied in the usual way, and the insulators are set on steel bolt pins about 9 in. long. The line runs through a country in which lightning storms are frequent but not exceptionally severe. Interruptions of service have occurred during thunder storms, and usually two insulators on the opposite ends of the same arm would be found punctured from the tie-wire to the pin. The interruptions became so frequent that it was necessary to make some change, which had to be done without disturbing the working of the line; this left about two hours each night available for work, and the owners of the line were not prepared to incur any heavy expenses. Accordingly, half the cross-arm braces were removed, leaving on each pole a brace from the pole to one end of the cross-arm only, and wooden pins about 15-in. long were substituted for the steel pins, using the same insulators.

After this change the interruptions of service due to lightning were diminished from an average of two or more a month to about the same number during the season following the change. Several cross-arms were burned off, but caused no suspension of service at that time.

Geo. T. Fielding, Jr.: Incidental to the main subject of Mr. Scholes' paper, I would like to arouse some discussion on one of his assumptions: namely, that of allowing for one-half inch of sleet upon the conductor. As a matter of common interest, it would be profitable to learn if any one here has ever seen sleet upon a transmission line that was carrying power or even charging current, and also if there was any wind at the time this occurred. This is an old question perhaps, but we have had experience enough now to cease basing calculations upon advance assumptions that were made for the first lines erected. The greatest mechanical stresses on transmission lines are due to high winds, and a small increase in the diameter of the conductor, as occasioned by a coating of sleet, results in a considerable increase in the imposed stress. The assumptions made, as regards sleet, therefore very materially influence the allowable sags and tower-heights, and while it is legitimate to favor conservatism, it is questionable if we are not inclined to be over-liberal.

I notice that Mr. Rowe uses a stranded steel cable for the ground-wire. This has been the practice on a number of lines. On account of its short life and tendency to stretch and sag, one of the larger telegraph companies has recently ceased using stranded cable for guy- and messenger-wire service. The old solid No. 3 steel galvanized wire is now being substituted in its place. It seems quite reasonable that the cable should tend to retain moisture, by virture of its strands, and hemp center if it has any. This moisture is not helpful in preserving the metal against rust.

Mr. Rowe seems to have had considerable trouble with puncturing of the insulators. This experience has been repeated on many other transmissions. On steel-tower lines where disturbances cause local and suddenly excessive potentials or frequency, the insulators are often observed to puncture before they will arc over, due probably to the element of time which is necessary for the potential to distribute itself.

Increasing the thickness of porcelain does but very little toward increasing its resistance to puncture. It appears as if the use of larger insulators is not the solution of the problem; that is, it is not enough simply to install insulators of larger dimensions, insuring merely a greater arc-over capacity. It is essential to separate the live conductor and the ground, the pin, by a greater distance than has heretofore been specified to obtain reliable insulation: this has been accomplished by the suspension method, described in the paper by Mr. Hewlett. We shall be compelled to direct our efforts with this principle in view before we can successfully operate at, or above, 100,000 volts.

N. J. Neall: One point in Mr. Rowe's paper is, in my judgment, misleading; that is, the use of a circuit-breaker attachment in the neutral of the transformers. In any three-phase transmission line with grounded neutral, the puncture of even a single insulator is more than likely to result in the fusing apart of the conductors, so that in this particular instance any disturbance of this character would undoubtedly seriously impair the continuity of service. I have seen this fusing take place in suprisingly quick time and realize perfectly what it means on service. Now the conclusion to be drawn from Mr. Rowe's paper is that the additional line protective apparatus, irrespective of the automatic cut-out, has been the chief benefactor in this case, but this seems to me a very doubtful conclusion. In other words, the important result is that a *combination* of these things—overhead ground protection, larger insulators, and automatic cut-outs, has produced the desired improvement.

Ralph D. Mershon: The assumptions as to sleet, wind, and various other things which should be taken care of in the design of a transmission line are questions on which engineers will differ almost as much as on the subject of the use or non-use of choke coils. It seems to me that the general solution presented by Mr. Scholes is a very admirable and satisfactory one. There are some points in it to which exception might be taken, but if all the refinements are gone into, such general solution would become so complicated that its value would be questionable. The value of this general solution is that by sorting general assumptions, one can arrive at a preliminary idea as to what is going to be the best plan, considered from the standpoint of those assumptions, and that this preliminary idea will serve as a guide in adapting the construction to meet other considerations, such as inequalities of the country, the desirability of having fewer points of support, etc.

I shall be interested to hear from Mr. Scholes as to the cost in proportion to weight.

Mr. Rowe's experience with grounded wires does not enlighten me much. It does not seem to me that he has offered any definite evidence that the grounded wires do a great amount of good. In the plant of the Niagara, Lockport and Ontario Power Company, we are trying to avoid the use of the grounded wire on account of the expense of putting it up. We are installing on the top cable—there are only three cables, carried on the tower in the form of an equilateral triangle—what amounts to a horn lightning-arrester, a grounded horn reaching far enough above the tower to serve also as a lightning-rod. During the last few days we have had worse storms than we had last year, and the results, so far as we have been able to analyze them, seem to show that these line structure lightning-arresters, as we call them, have been of great value. Their value could be greatly augmented by increasing their number. They are now spaced at approximately 2200 ft., and are set for a discharge gap of 6 in. This discharge gap will be reduced to 4.5 in. or, perhaps, even to 4 in.

Some of our experiences seem to show that lightning does not travel along the line. During one of the storms the last two or three days, we have had three insulators punctured between two of the line structure lightning-arresters. The lightning chose to puncture an insulator rather than travel 550 ft. to go over the 6-in. gap. Possibly, when we reduce the size of the gap, we can cause the lightning to travel.

I am not much of a believer in the idea of being able to foretell what is going to happen in the matter of lightning, whether the prediction involves the nature and contour of the country or the apparatus concerned. We now have, I believe, about 400 miles of main line; 80 miles of this is in rough country, the rest of it is over country that is practically flat. In the flat country the lightning is at times perfectly fiendish, so that, if there is any connection between lightning and mountains, there is nothing on our transmission line to indicate that such is the case.

We do not transpose our lines. We had some transpositions, but found they could be taken out, and have taken out almost all of them. We intend to confine the line structure lightning-arresters to the top wire, in order that when it operates our service will not be interrupted; since, if there are line structure lightning-arresters on two or more of the cables, and two of them operate simultaneously, a short-circuit will result. Whereas, if the lightning-arresters are confined to one of the cables, and we have a resistance in the neutral of the generating station, the arc will clear itself without necessarily interrupting the service. If we transpose and endeavor to follow out this idea, the line structure lightning-arresters would have to be, in some instances, on the top cable and in some instances on one or the other of the cross-arm cables. It may be that, before we get through, we shall put line structure lightning-arresters on more than one cable; but, judging from the performance of the line structure lightning-arresters with a 6-in. gap and spaced 2200 ft. apart, as is the case at present, this will not be necessary. In the last three severe storms, one of which was worse than anything we ever had before, the present installation of line structure lightning-arresters has done much good.

The sub-station lightning-arrester equipment is the one which Mr. Stott has designated as the "totem-pole" equipment. There are nine horn lightning-arresters to each three-phase circuit, three to each conductor of the three-phase circuit. One of the three is set for a large gap and high resistance, the next for a higher gap and lower resistance, and the next for a still higher gap and that has a fuse. So far these arresters have afforded full protection. They have discharged frequently. There are no choke-coils.

N. J. Neall: In your line arresters do you get a continued arc because of the resistance in the neutral, or is it the customary charging arc which you get if you ground one leg of the railway system?

Ralph D. Mershon: We have the neutral grounded through a resistance, and think the line arresters will behave in a good deal the same way as the intermediate arrester used at a sub-station having an intermediate gap, and which has 1000 ohms in series with it.

D. R. Scholes: It must be borne in mind, in considering this problem, that it is impossible to choose a single set of assumptions which will be satisfactory for all lines. Varying climate, contour of country, and other varying conditions of this nature make it impossible. The making of such assumptions in the paper is incidental to the main object of the paper.

It is to be observed that the method pursued in the paper is first to derive an equation expressing the relation between the weight of a tower of given design and its height and strength. This expression is almost wholly accurate. An example illustrating its application to a practical case is then given. In the example certain assumptions are made use of. It is expected that such assumptions will, in each case, be made to suit the particular conditions that are being dealt with.

Most of the discussion, however, has had reference to these assumptions, and while it is not important that their accuracy be proved, the following may be said in support of them: It is assumed that the towers may be had at a given price per pound. This may not always be the case, but, within the range of ordinary practice, manufacturers are to be found who will contract for such structures at a given price per pound, before the size or strength of the towers has been definitely fixed.

It is assumed that the cost of a foundation will vary directly as its volume. The foundation cost will, of course, largely depend on the local conditions. Inasmuch, however, as the economical span will almost always be between 400 and 800 ft., and since the size of the foundation required will not change greatly between these limits, such an assum tion seems admissible in the present instance.

The builder of steel towers for transmission lines is apt to find that the variety of assumptions regarding wind, sleet, factor-of-safety, etc., with which he has to deal is almost as great as the number of different engineers with whom he comes in contact. Each engineer seems to have a different set of natural conditions to meet. The severity of his assumptions seems to depend, generally, on how much money his company can afford to spend on towers. Now it is manifestly impossible to give mathematical expression, in advance, to factors which vary from causes of this sort. So the paper aims to put in the hands of the engineer in charge of line construction a formula which will show the effect on the tower-cost of any change in assumption he may contemplate, and which will make possible a simple solution for the economical span on the basis of his own assumptions.

Frank G. Baum (by letter): Mr. Scholes finds a shorter span more economical than is generally supposed to be the case. It would be of interest had he drawn two curves showing the cost of tower structures, one using his assumptions of sleet or snow on the cable at time of maximum wind velocity, the other with no sleet or snow. In a large section of the country sleet and snow need not be taken into account in the calculations.

Farley Osgood (by letter): Will Mr. Rowe please say whether with complete overhead grounded wire and lightning-rod installation, the use of time-limit relays on the outgoing transmission lines, is recommended, or whether instantaneous relays are preferred?

It is believed that a lightning-arrester installation about 75 miles from the power-station would help the system to a considerable degree, especially if the proper type of electrolytic arrester is used, which has been proved to be very efficient in cutting off the crests of surge-waves.

Would Mr. Rowe recommend the use of an overhead grounded wire on a wooden pole line, to be grounded at every pole by a suitable ground wire running down the pole?

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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A NEW TYPE OF INSULATOR FOR HIGH-TENSION TRANSMISSION LINES

BY E. M. HEWLETT

Link Insulators. Suspension and Strain Types

The transmission of large amounts of power over long distances has reached such proportions that the voltage necessary to transmit this energy makes the problem of line insulation difficult. The so-called "pin" type of insulator has been enlarged to meet the greater demands until it has approached, if not already passed, the limits of good construction. Mr. Buck has given this matter a great deal of study in his high-potential transmission work, and, being dissatisfied with the mechanical features of a pin insulator, has devised a method of line construction involving the use of "suspension" and "strain" insulators. The suspension insulators support the line from above, hanging vertically beneath the cross-arm (or other point of suspension). The strain insulators are used at turns and at intervals of, say, every mile, to support and "anchor" the line, also as pull-off insulators on curves and to dead-end lines.

It is intended in this paper to give some mechanical and electrical tests and describe a porcelain insulator which the writer has designed to carry out this method of supporting high-potential transmission lines.

Each insulator unit is a flanged, or a petticoated, disc with an enlarged central portion having two interlinked semicircular holes. It is called a "*link insulator*" because it is used to insulate the interlinked tie-wires. The holes in the insulator are so arranged that the tie-wires which pass through them exert a compression strain on the porcelain (Fig. 4). Should the insulator

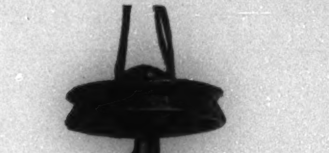

Fig. 1

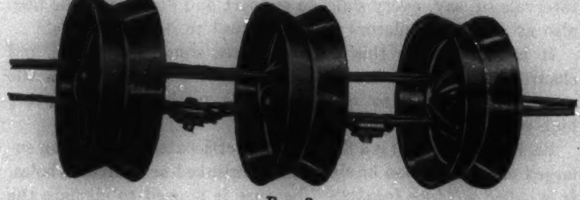

Fig. 2

break, the tie-wire loops would still be intermeshed (Fig. 5), and as the discs are used in series, with a factor of safety, the remaining discs prevent a ground being formed until the break can be repaired. The link insulator for suspension (shown in Fig. 1) is a petticoated disc, while the strain insulator (Fig. 2) is a disc with a grooved flange. The mechanical and electrical features of the two forms of insulators are essentially the same. The petticoats and flanges are so arranged that one side of the insulator is always protected from rain.

A diameter of 10 in. for both types of insulators has been found by experiment to be most convenient, and such insulators are suitable for a working voltage of 25,000 volts per disc. For higher potentials the disc sare placed in series; for instance, four 10-in. discs are suitable for a 100,000 volt line. As the separate discs arc when wet at approximately 65,000 volts, the rated voltage of 25,000 volt is within safe limits. The 10-in. discs were tested for strength and supported a load of three tons.

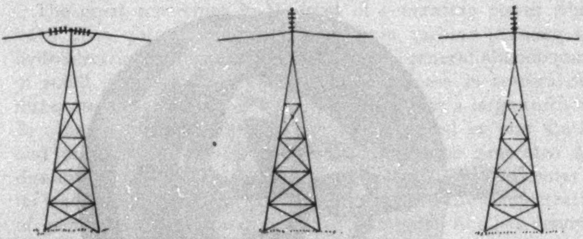

FIG. 3

The insulators described above being made of one piece of porcelain, no cemented fittings or sections are necessary. They are not affected by extreme heat or cold, having stood the test of a severe winter. Tests prove that an insulator with sheltered surfaces stand, a much higher rain test than a much larger insulator which has no dry surface, as for example, a flat disc without the flange or petticoat.

Fig. 3 shows a possible method of line support using ten towers per mile, in which the line is anchored at the end of each mile and at curves, and suspended at intermediate towers. From the cut it will be noted that the conductor is looped around

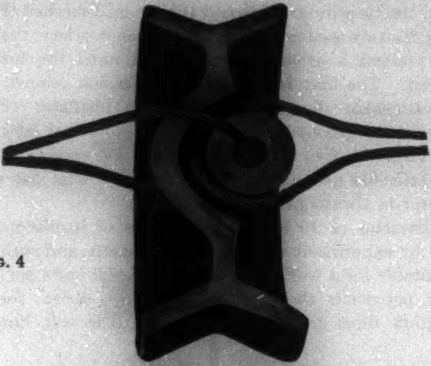

FIG. 4

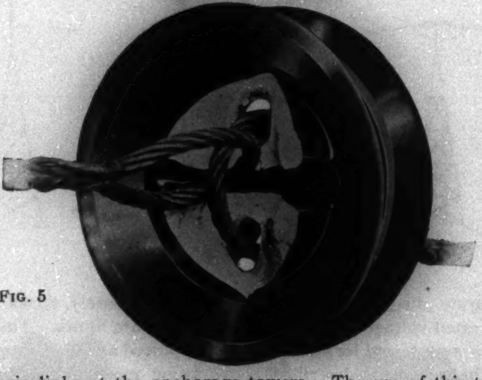

FIG. 5

the strain links at the anchorage towers. The use of this type of insulator does away with torsional strain on the cross-arms, giving it a decided advantage over the pin insulator. It is obvious that the link insulator is adaptable to a great variety of conditions.

Fittings have been designed for use with these insulators to fit the conditions thus far presented, but each case should be considered as it comes up, and such fittings designed as are necessary.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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SOME NEW METHODS IN HIGH-TENSION LINE CONSTRUCTION

BY H. W. BUCK

The great economies in the cost of generating power which have been obtained in the large steam turbine stations and hydroelectric plants, are leading to the general abandonment of small generating stations and the increase in transmission distances in order to distribute power over a large territory. In other words, 100,000 h.p. can be generated in one station and transmitted 100 miles cheaper than it can be generated and distributed from ten 10,000-h.p. stations each near the center of its load. On account of this tendency toward the concentration of generating units, the overhead transmission line has assumed a position of great importance in electrical installations, and the same permanency and reliability is demanded of it as of the generating station itself. The wooden pole line of the past has been practically abandoned and steel construction has been substituted.

The long distances covered by many of the modern lines, the large amounts of power to be transmitted, and the very high price of copper and aluminum—all have combined to force up the transmission voltage to the highest practicable limit. In consequence, the demand for high-voltage overhead line insulators has outgrown the present standard practice, and some new systems will have to be introduced to meet the new conditions.

The method of line construction here described has been developed by the writer and Mr. E. M. Hewlett and is believed to offer a means of operating lines safely at higher potentials than is practicable with insulators of the pin and petticoat type.

Fig. 1 illustrates in a diagrammatic way the arrangements for one circuit. The tower supports shown here are those which were used merely for experimental work and need not be considered as a commercial design. Each span is dead-ended at each support as shown, through a series of insulating units which in this case are plain discs connected together with steel links. The various spans are then electrically connected by jumpers hung below the insulators. The insulators are directly attached to the cross-arms, eliminating all pins. The number of discs linked together in series depends upon the line voltage, the discs themselves being identical for all voltages.

Fig. 2 illustrates a design for a 100,000-volt two-circuit line which is soon to be constructed for transmitting 50,000 h.p. 165 miles. The spans in this case will range from 500 to 1000 ft. in length. Here the line is suspended below the cross-arm on most of the towers. The lines will be dead-ended with jumper connection, as shown, only at angles and on tangents at about every fifth tower. This dead-ending will be for the purpose of stopping any creeping of conductors on the line as a whole, to check the transmission of longitudinal waves along the conductors due to wind, and on curves to take the side stress of the conductor due to change in direction. In this installation the lines will not be triangulated, but at suitable intervals along the lines the conductors will be transposed so as to balance up effects of mutual static and magnetic induction. Special cross-arms will be installed at transposition towers.

Fig. 3 illustrates another design for a two-circuit line which is to be built for 80,000-volt operation. The spans in this case will range from 300 to 400 ft. and the conductors will have an approximately triangular relation. The conductors will be suspended by a series of insulators from the cross-arms as in Fig. 2 with occasional rigid attachment, for the reasons given above.

ig. 4 shows a method of assembly of the insulators for suspension under a cross-arm. Fig. 5 illustrates a method of assembly where spans are dead-ended at the cross-arm with jumper connection.

The advantages of this construction, which might be termed "series unit insulation," over the pin and petticoat type may be summarized as follows:

a With the standard type of pin insulator now used the difficulties of construction increase very rapidly at the higher voltages. The cost of insulator for a given margin of safety increases for voltages above 60,000 nearly as the cube of the increase in voltage. Either very large petticoat diameters must be used, or very high insulators with many petticoats. In either case the manufacture of the porcelain parts is a difficult and expensive matter, and with the long pin necessary, the mechanical stresses from the line on insulator, pin, and cross-arm are objectionable. With the series unit system here proposed, the cost of insulator progresses only in direct proportion to the increase in voltage, the only change being in the number of units in series. There is practically no limit to the degree of insulation obtainable.

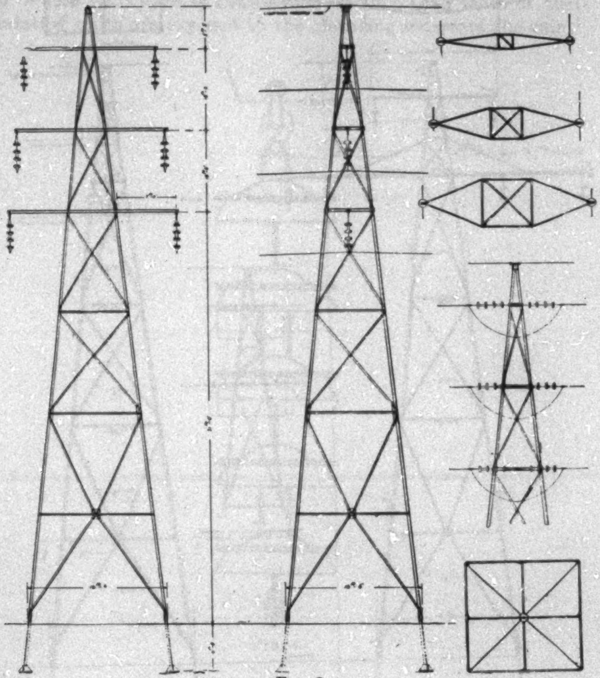

FIG. 2

b One of the most difficult elements of design in a transmission tower, where long pins and petticoat insulators are used, is to obtain a cross-arm which will resist the torsional stresses due to the

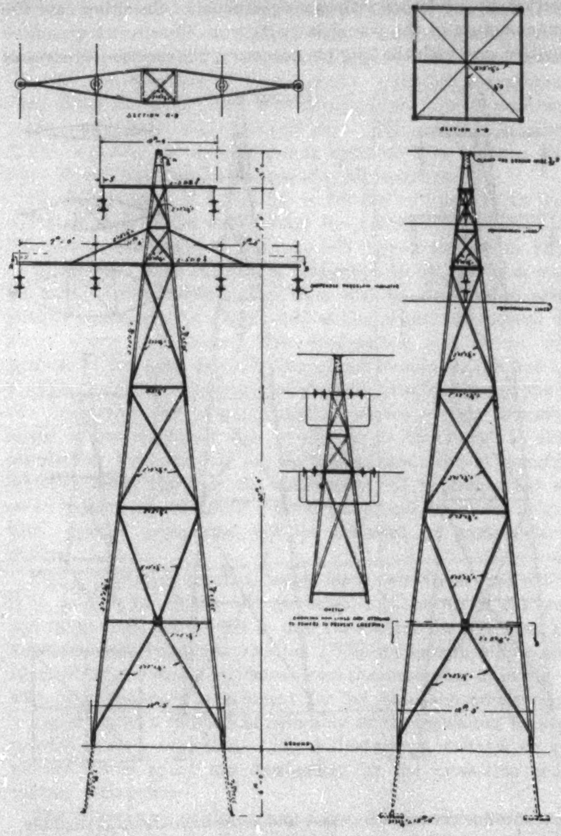

FIG. 3

leverage of the pin. With the pin entirely eliminated, the stresses are directly applied to the cross-arm; this cheapens the construction of the tower.

c In the arrangements shown where the insulating units are attached on either side of the cross-arm, taking the full tension in the line with jumper connection between spans, the insulation can be increased indefinitely by adding discs in series without increasing the space occupied on the tower.

d Where each span is dead-ended, as in (*c*), all faces of the insulating units are exposed to the cleansing action of the rain, so that dirt cannot accumulate thereon. This arrangement also prevents the dripping water from forming electrical communication between units as occurs from one petticoat to another in the pin type of insulator.

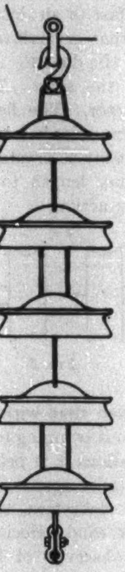

FIG. 4

e A standard insulating unit can be adopted for all voltages, the only variation being in the number linked in series. This simplifies the manufacturing problem.

f If any insulating unit becomes damaged or completely shattered, the insulation of the remainder is not affected. The damaged unit can be replaced without the necessity of renewing the whole.

g If a tower is directly struck by lightning the cross-arms will be likely to take the discharge, since they are above the lines, whereas in the pin type of insulator the line is usually the highest point.

h In long-span installations where the conductor at each end of the span is tied fast to an insulator mounted on a pin, experience has shown that crystallization is apt to take place in the conductor at the tie, due to its rigidity at that point and the vibrations in the span. This frequently results in breakage of the conductor. The flexible connection between conductor and cross-arm afforded by the series of insulators should reduce this tendency to crystallization, and should therefore permit spans of any length to be used without further precautions against this action.

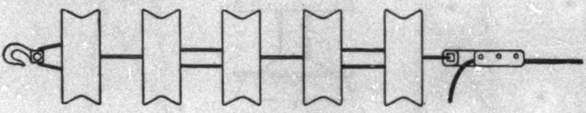

FIG. 5

Fears may be expressed that with the conductor suspended under the cross-arm serious swinging to and fro might take place. From numerous observations it is believed that no such swinging will occur. Long aerial spans under wind pressure take a permanent and steady deflection throughout the span proportional to the average wind velocity along the span, and no indications have been observed of long spans responding to so-called gusts. The towers shown in this paper are designed so that the conductor can safely be deflected by the wind about 60° on either side of the neutral position.

Insulators of a great many forms have been built and tested, but the one which gives the best results electrically and mechanically is the link type developed by Mr. Hewlett and having the grooved or fish-tail periphery. Four of these in series are sufficient for 100,000-volt operation with a liberal factor of safety.

A very important element in this construction is of course the methods of fastening the insulating units together and attaching them to the line and cross-arms. This can be accomplished in many ways and several methods have already been worked out, but these details are beyond the scope of this paper. Further experience in practical line construction and operation under this system will demonstrate the best methods of installation and attachment.

DISCUSSION ON "A NEW TYPE OF INSULATOR FOR HIGH-TENSION TRANSMISSION LINES," AND "SOME NEW METHODS IN HIGH-TENSION LINE CONSTRUCTION", AT NIAGARA FALLS, N. Y., JUNE 26, 1907.

J. B. Whitehead: Have any tests been made to determine the potential over these insulators when placed in series? Is the actual distribution 25,000 volts per unit?

Ralph D. Mershon: The more I consider Mr. Hewlett's type of insulator the more attractive it is from many different standpoints, but I should like to know if Mr. Hewlett has constructed any spans. using these insulators, with the idea of finding out just what sort of mechanical oscillations or waves, or swinging can be obtained. It seems to me that there is a possible chance of these spans swinging so as to arc to the tower. There does not seem to be any chance to use a discharge gap in connection with a line. Any arc close to the insulator has a good chance to destroy the whole insulator whereas if there were a discharge gap, the arc would rise away from the insulator and it could be saved. It would be extremely difficult to install a line using such insulators and more difficult to repair it.

Ralph W. Pope: This appears to be one of the cases where there is a decided improvement in insulators, with some objections due to manufacturing, which may be eliminated as we go along. It is likely that in the course of time, with greater experience with the insulator, these difficulties may be overcome. Is it not the case with most improvements, that in practice the shortcomings are eventually overcome ?

Ralph D. Mershon: For about three years past we have been conducting some high-voltage measurements in Niagara Falls, under all the various conditions we could think of that would approach actual practice. We took a lot of actual loss measurements on insulators of different sizes, dry and wet. I thought that if we assumed a certain thickness of the films on the petticoats of the insulators, and calculated on that assumption the resistance from the neck of the insulator to the pin, perhaps we could get some relationship between the loss over insulators of various sizes. It would not work out. Some of the smaller insulators had less loss than the big insulators. I think that the petticoats become charged and act as a condenser plate with reference to the pin. and the closer they are to the pin the more effectively the condenser acts to increase the loss and make them flash over. We measured the loss from the neck of an insulator to the pin, with a wooden pin and a metal pin. The wooden pin, if dry. gives fine insulation, and at first thought one would think the loss would be lower with the wooden pin than with the iron pin; but it was a great deal higher. This surprised me. I thought it over and finally reached a probable solution, and this solution has been confirmed by another experiment. The way I explained the higher loss is this: the insulator is taking a certain charging current; the pin has a straight ohmic resistance; and the voltage taken by it is in quadrature with the voltage of the supply current. You might increase the I^2R considerably, without decreasing the current going over the pin. We got a wooden curtain pole, and stuck the insulator on that, and took different lengths of pin. After the first trial it was found that the loss continually fell off as the length of the pin increased.

F. B. H. Paine: There are some features of transmission engineering which are not altogether electrical. The people along the line are likely to insist on having a method of supporting the cables which will prevent them from falling to the earth, or so close to the earth as to become a menace to travelers on the highway because of the loss of one or more points of support. If the cable is supported from above, it will necessitate some means to catch the cable in case an insulator fails and the cable is lowered. Is this provided for in this design ?

Chas. P. Steinmetz: In multigap lightning-arresters very great inequalities exist in the potential distribution only when very many spark gaps are connected in series across a high-potential circuit. With four or five or even ten spark gaps in series, the distribution of potential under lightning-arrester conditions is still practically uniform. There is to be considered, regarding this distribution of potential, between the successive insulator discs the fact that it is a function of the voltage and that when voltage is raised to a point approaching the breakdown strength of one element, then the distribution of the potential changes and becomes more uniform. So it may well be, if there are, say, four elements in series, you get across the first element 50 per cent. instead of 25 per cent. of the total voltage at normal impressed voltage. If now you increase the potential, as soon as it approaches the breakdown strength of the first element, brush discharges occur over the surface etc., and to increase the effective capacity of this condenser, and then the potential distribution becomes more uniform and may be nearly uniform, when you reach the united breakdown strength of the whole system, at least where the number of sections is not very large.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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THE TRANSMISSION PLANT OF THE NIAGARA, LOCKPORT AND ONTARIO POWER COMPANY

BY RALPH D. MERSHON

On the seventh day of July, 1906, there was put into operation the first of the transmission lines of the Niagara, Lockport and Ontario Power Company. This event marks the inauguration of one of the first undertakings in the matter of distributing Niagara power over a large section of country, and the beginning of an enterprise which is one of the most important, and in some respects the most important, of its kind anywhere in the world.

The plans realized at present and contemplated for the immediate future, in the plant of the Niagara, Lockport and Ontario Power Company, involve a maximum transmission distance of 160 miles. This distance puts the plant amongst the longest transmissions of the world. As regards capacity, the plant of the Niagara, Lockport and Ontario Power Company is now one of the most important in existence, and, in the near future, its capacity will be far in excess of any other transmission system in the world. In addition to these points of importance, there are a number of engineering features somewhat out of the usual line of transmission practice which make the installation of interest from an engineering standpoint. Inasmuch as the description of such a plant is usually more satisfactorily accomplished through pictures than otherwise, they will be mainly resorted to herein, with the aid of only such brief text as may be necessary to cover points which cannot be well shown in illustrations.

The prospective system of the Niagara, Lockport and Ontario Power Company is a comprehensive one for the delivery of power in the United States within an economic transmission radius of Niagara Falls, and especially for its delivery in the northern and western portions of the state of New York. The company expects within the next two years to be transmitting 60,000 horse power, and its present right-of-way purchases are with reference to an ultimate transmission of 180,000 horse power. The plans of the company as at present laid out contemplate the transmission of this power by means of main lines and branch lines therefrom; the contracts for power being, wherever possible, made for delivery of the power at the main-line voltage of 60,000, less line drop. Where, however, the business of a given territory will justify it, the company will install step-down transformer stations for the delivery of power at a lower voltage. Each of the main transmission circuits will be capable of receiving and transmitting 30,000 horse power at 60,000 volts, and it is intended always to provide a sufficient number of spare main transmission lines to insure continuity of service on the main line. Spare lines will be provided in the case of branch lines only when the latter are of considerable importance.

The Niagara, Lockport and Ontario Power Company is only a transmission company; that is, it buys the power to be transmitted and has, therefore, no generating plant of its own. The power for the transmission is generated in the hydraulic power station of the Ontario Power Company, situated on the Canadian side of Niagara Falls. The water for this station is taken from the Niagara River, some distance above the falls, whence it is brought to a point at the top of the cliff, a short distance below the falls, through underground steel conduits, and from this point delivered through underground penstocks to the power station located at the bottom of the cliff, near the foot of the falls.

The power house contains the generating units with their exciters and switchboard apparatus. The generators have a capacity of 7,500 kw. each, and deliver three-phase 25-cycle current at 12,000 volts. From the power station the current is taken at 12,000 volts to the transforming and switching station of the Ontario Power Company located on the bluff above the falls. It is stepped up from 12,000 volts to 62,500 volts, and at this latter voltage delivered to the transmission lines. The transmission lines of the Ontario Power Company extend from its transforming station to a point some six miles farther down the Niagara River, at which point the

Fig. 1—Niagara crossing, general view

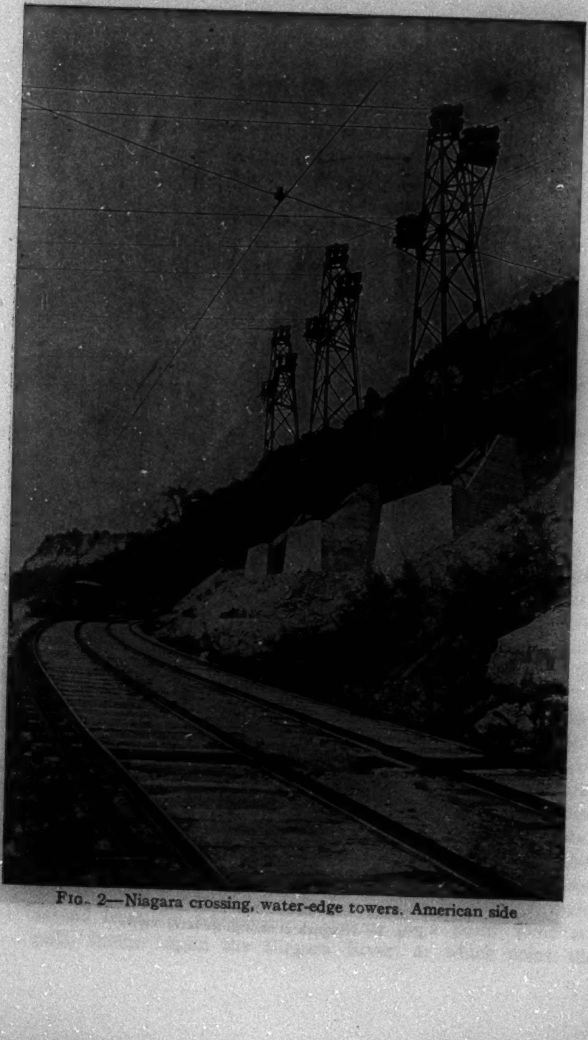

FIG. 2—Niagara crossing, water-edge towers, American side

lines connect to circuits spanning the Niagara River. The Niagara, Lockport and Ontario Power Company takes delivery of the electric power at the international boundary line in the middle of the Niagara River.

At the present time, the Niagara, Lockport and Ontario Power Company has in its possession a private right-of-way 300 feet wide from the Niagara River to the town of Lockport, about 16 miles east; from Lockport east to Mortimer (six miles south of Rochester), a private right-of-way 200 feet wide, a distance of about 57 miles; from Mortimer to Fairport a 100-foot private right-of-way a distance of 10 miles; and from Fairport to Syracuse a private right-of-way 75 feet wide, a distance of 71 miles. From Lockport south, in the direction of Buffalo, the company has a private right-of-way 100 feet wide. In ad-

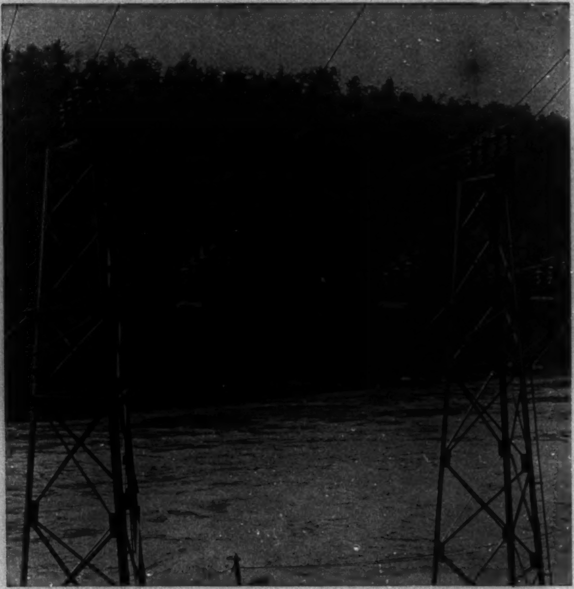

FIG. 3—Niagara crossing, top of water edge towers

dition to this, the company has the right to install transmission lines on the right-of-way of the West Shore Railroad and has acquired the necessary private right-of-way to get from its main private right-of-way to that of the railroad company.

The installation which the company has now in operation is for receiving 30,000 horse power and delivering this amount, less the line loss. The main transmission consists of two lines in duplicate. From the Niagara River to Lockport, a distance of 16 miles, there are two lines on the company's private right-of-way, each capable of transmitting 30,000 horse power. From Lockport to Mortimer, a distance of 57 miles, there is a line on the company's private right-of-way having a capacity of 20,000 horse power. From Mortimer east to Syracuse, a distance of 81 miles, there is a line on the company's right-of-way

FIG. 4—Niagara crossing, cantilevers, American side

having a capacity of 10,000 horse power. From Lockport to a point about 11 miles east, thence south on the company's private right-of-way to the West Shore Railroad, and thence on the West Shore Railroad to Pittsford is a line having a capacity of 20,000 horse-power. From Pittsford on the West Shore Railroad right-of-way east to Syracuse is a line having a capacity of 10,000 horse power. From Lockport south to a point south of Buffalo, there are two transmission lines on the private right-of-way of the company, each having a capacity of 30,000 horse power. These two lines south are tapped into the two lines

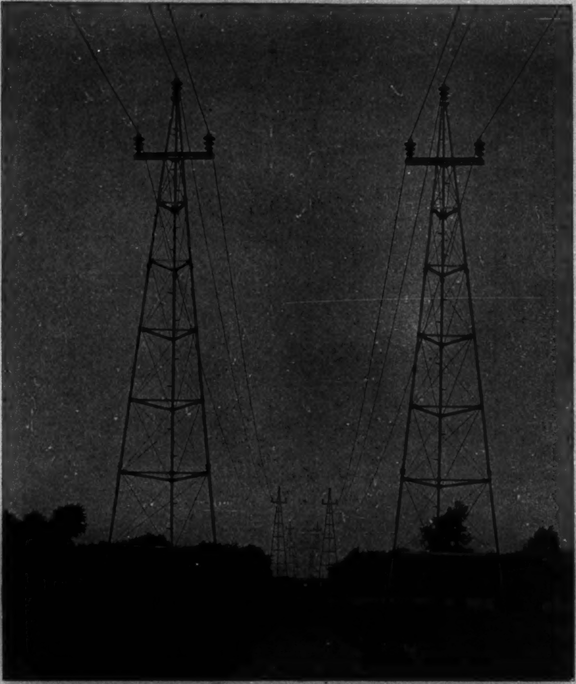

FIG. 5—Pipe towers

FIG. 6—Transmission lines from Lockport to Buffalo

coming from the Niagara River to Lockport, and constitute, therefore, at present, a branch line; but they will be eventually extended clear through to the Niagara River, and it is in anticipation of this extension that they are constructed with the full capacity of 30,000 horse power. As will be seen from the above, the distance from the Niagara River to Syracuse is 154 miles. In addition to this, the transmission from the transforming station of the Ontario Power Company to the Niagara River has a length of about 6 miles, making, as previously mentioned, a maximum transmission of 160 miles.

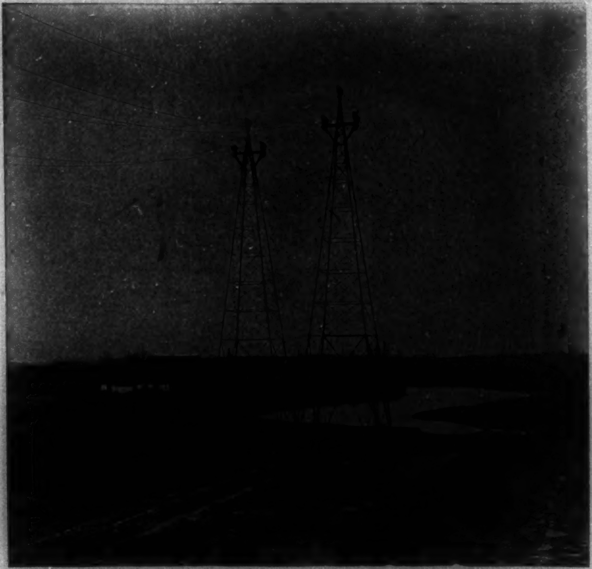

FIG. 7—950-foot span over Buffalo creek

It will be seen, therefore, that in delivering power in Lockport, and in the neighborhood of Buffalo, Rochester, Syracuse, and at intermediate points, the company will have transmission circuits in duplicate, each capable of transmitting the full amount of power to be delivered at the several points.

As previously stated, the power is brought across the Niagara River by means of aerial cables spanning the river, and delivery of the power is taken by the transmission company at the international boundary line. The cables are brought across the river in three spans; one span from steel cantilevers at the top of the cliff on the Canadian side to steel towers at the water's edge on the Canadian side; another span from the water-edge towers on the Canadian side to the corresponding towers on the American side; and a third span from the steel water-edge towers on the American side to the steel cantilevers at the top of the cliff on the American side. The use of cantilevers is necessitated mainly by reason of the steep angle at which the cable descends from the top of the cliff. Their use also makes possible the required clearance between the cable and the slope of the gorge, a point of special importance on the American

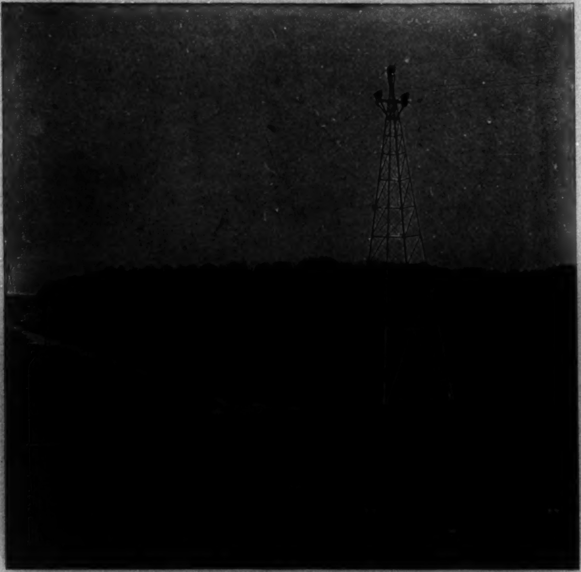

FIG. 8—1253-foot span over swamp

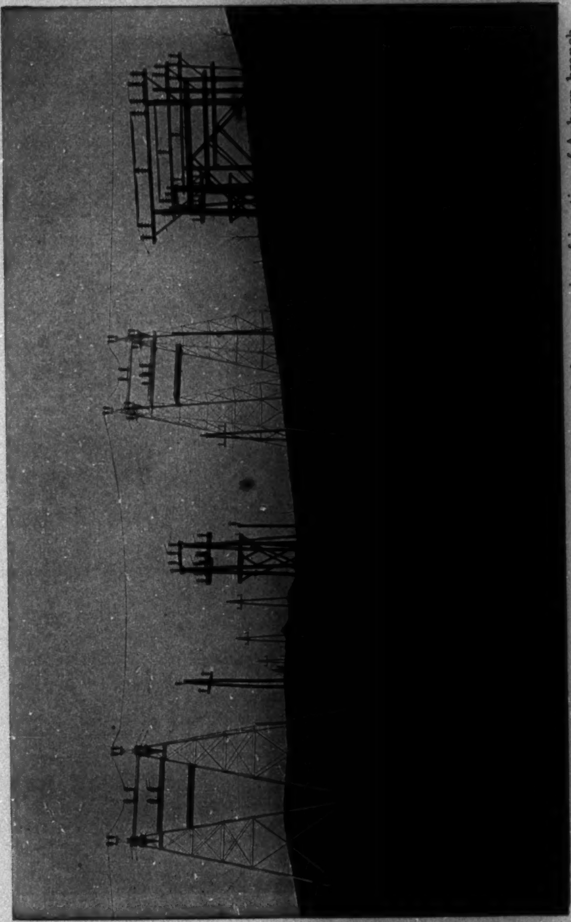

FIG. 9—Cross-connecting and disconnecting switches and open-air fuses at point of junction of Auburn branch line and the main line

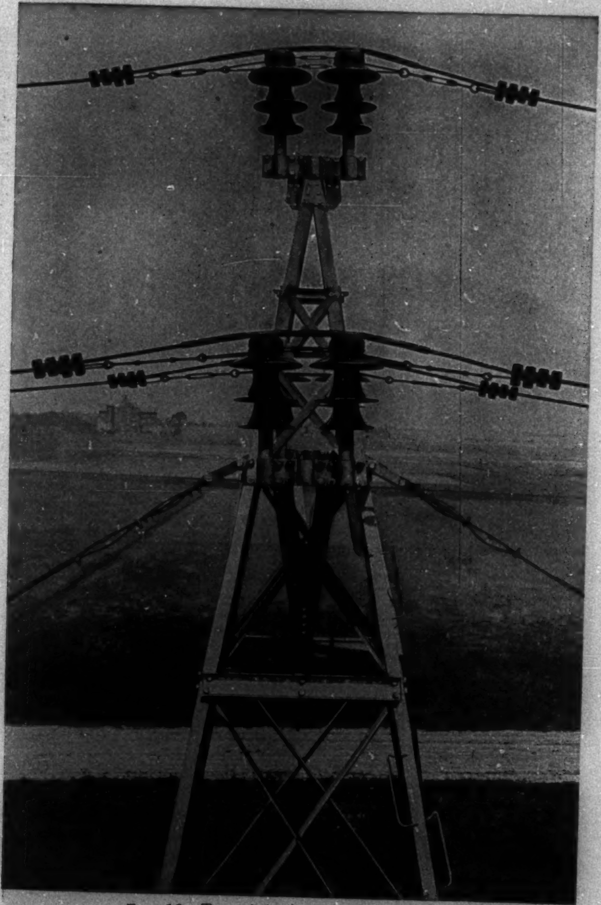

FIG. 10—Top of double-guyed steel tower

side in view of the fact that one of the branch lines of the New York Central Railroad is on the American slope of the gorge. The steep slope of the cable at the cantilevers would make it bear upon the upper petticoat of the insulator supporting it, if the cable were attached to the top of the insulator in the usual way. As will be seen by the photographs of the cantilevers, this difficulty is obviated by attaching the cable to a steel cross-bar supported at each end by an insulator.

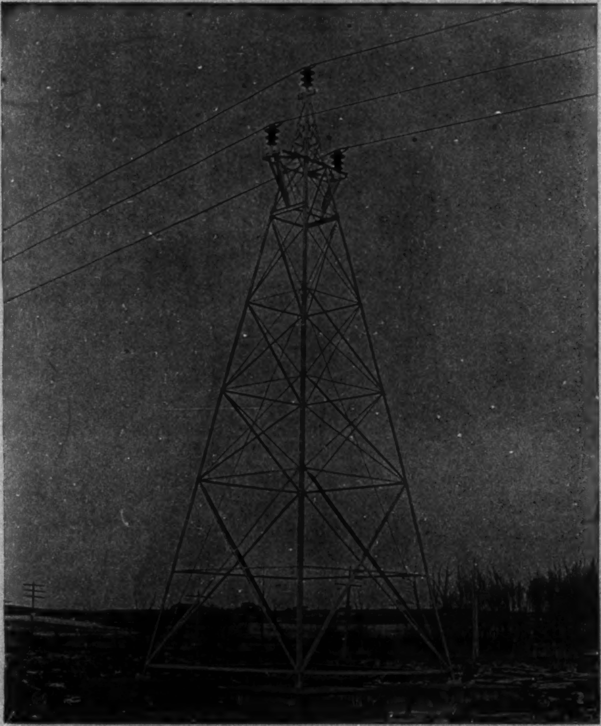

FIG. 11—Tower in Montezuma swamp

The steel cantilevers and the river-edge towers are all designed to withstand the most extreme conditions of sleet and wind that will probably ever exist. The requisite mechanical strength of the insulation at the points where the cables are attached to the steel structures is obtained by using a sufficient number of line insulators, and the proper distribution amongst these insulators of the forces which will come upon them is effected by means of malleable cast-iron caps cemented to the tops of the insulators and to which the cables are fastened.

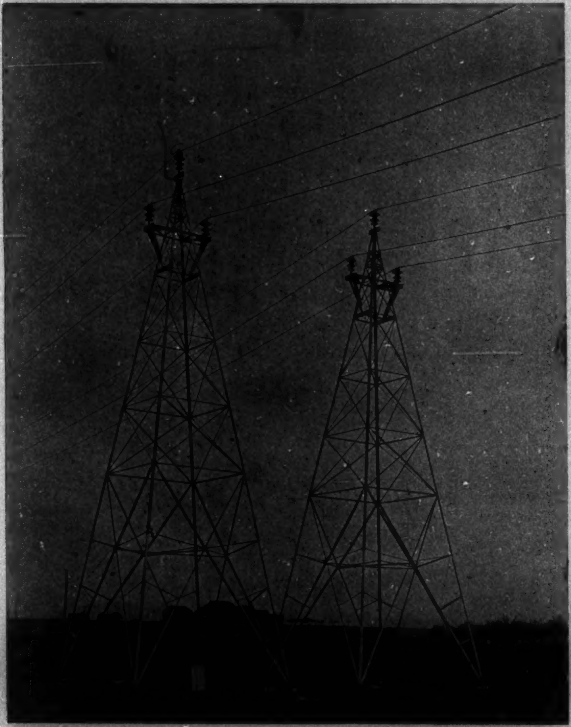

FIG. 12—Line structure lightning-arrester on steel tower

It was originally intended, and provided for in the contract with the Ontario Power Company, that just after crossing the river the 60,000-volt lines should be led into a switching station in which, by means of 60,000-volt electrically operated oil-switches, it would be possible to interchange the circuits coming into and going out of this station. The building itself for this switching station has been completed, but, before the equipment of the station had been installed, arrangements were made with the Ontario Power Company to defer the outlay for such equipment until the use of it should be more necessary than at the present time, when only two lines are in operation.

Fig. 13—Stringing line cable

The main-line construction of the Niagara, Lockport and Ontario Power Company is most substantial. With the exception of that portion of the main line on the West Shore Railroad between Churchville and Syracuse, the main-line structures are all steel towers, and the standard line-span is 550 feet. On some portions of the transmission line, however, much longer spans are used, the longest at present installed being 1,253 feet. In some cases these long spans had to be provided with towers heavier than the standard; in other cases it was possible to put them up with little, if any, modification of the standard tower construction. For a number of reasons, the principal one being lack of the requisite space, it was necessary to use on the West Shore right-of-way between Churchville and Syracuse wooden construction of special design which will be described later on, the standard span being 220 feet. In every case on the 60,000-volt lines, each line of towers or wooden structures carries only one three-phase circuit. The main line conductors installed so far are all of them of aluminum cable, except on a portion of the line between Mortimer and Syracuse where, because of the long spans employed, it is preferable to use copper.

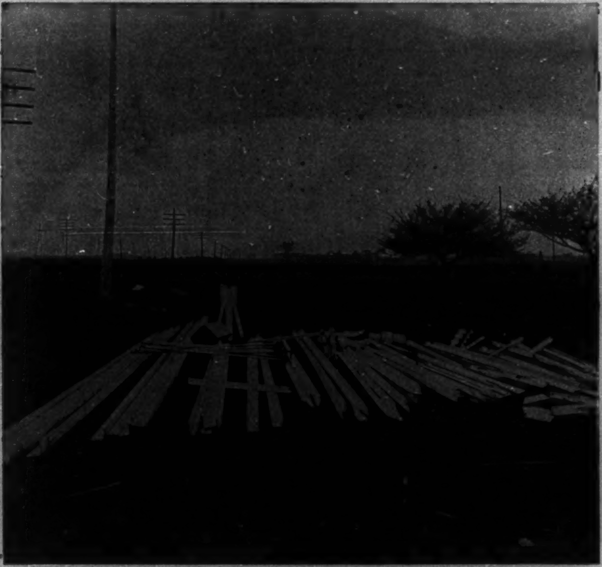

FIG. 14—Tower delivered ready for assembling

The first of the steel towers installed were of the tripod type, made of lap-welded pipe; but the later towers, and those which in the near future will be installed, are of structural shapes and galvanized. The design of these two types of towers is shown in the accompanying illustrations. Two types of the structural tower are shown. The earlier ones were non-interchangeable; that is, the guyed towers differed in construction from the unguyed towers. The later towers are interchangeable; that is, the guyed and unguyed towers are exactly similar except for the guys and double insulators of the former. Contrary to the practice which has heretofore been followed in the matter of steel line towers, the towers of this transmission line are mounted on foundations of reinforced concrete. These foundations are designed to utilize the weight of the earth around them in resisting uplift. The towers and their foundations are capable of withstanding transverse forces which will be brought upon them when the line cables are covered with 0.5 in. of ice all around them and the wind blowing transverse to the line at a velocity of 75 miles an hour. The towers have the same strength in all directions; that is, they are capable of withstanding the same forces in the direction of the line that they are capable of

FIG. 15—Assembling tower (1)

withstanding transverse to the line. To meet the contingency, not likely to occur, of all three cables breaking at once, in which case the full tension of all the cables might be brought upon the towers, there are at intervals along the line certain towers guyed both ways in the direction of the transmission line, and having double fixtures. The strength of these guyed towers is such as would enable them to withstand the forces that would obtain under the extreme conditions outlined above, if all the line cables should break. The guyed towers will, therefore, terminate any progressive failure of the line which might under extreme conditions be instituted by the breaking of cables.

FIG. 16—Assembling tower (2)

As stated above, on the West Shore right-of-way it was necessary to use wooden line structures. The type of construction employed is that which has been designated by the company as "A-frame construction." It is clearly shown in one of the accompanying cuts. By adopting this type of construction, in which each structure consists of two poles instead of one, it is possible to use twice the length of span that would be used in ordinary wooden pole construction and employ, therefore, one-half the number of insulators. As stated above, the standard length of span of this type of construction is 220 feet. On some portions of the West Shore right-of-way it was necessary to use steel construction, and in such places there were installed galvanized lattice steel poles, such as are shown in one of the illustrations. The span on these poles is the same as that on the A-frame construction.

FIG. 17—Foot of tower, showing method of fastening tower to foundation

In a number of places on the main line, both on the West Shore and on the private right-of-way, it is necessary to cross the Montezuma marsh. Where this marsh was crossed with steel tower construction, the concrete foundations for the steel towers were built by first excavating the swamp through the soft mud until the soft marl, forming the sub-stratum of the swamp, was reached. On the marl was laid a platform of two layers of corduroy, and on this platform was built the concrete foundations, the weight of which was made sufficient to take care of any uplift which will come upon the towers. These foundations were installed, some of them, in cold weather and, so far, they have shown no settlement. Where this marsh was crossed with A-frame construction, it was found in places much too expensive to excavate for the proper foundation for the A-frames. The A-frames were, therefore, installed by laying on top of the ground four line poles in two pairs, the poles of one pair being parallel to the line, and the poles of the other pair being at right angles to the line. These poles were spiked together at the point where they cross, and at the point of crossing the A-frame was spiked to them, the A-frame being further

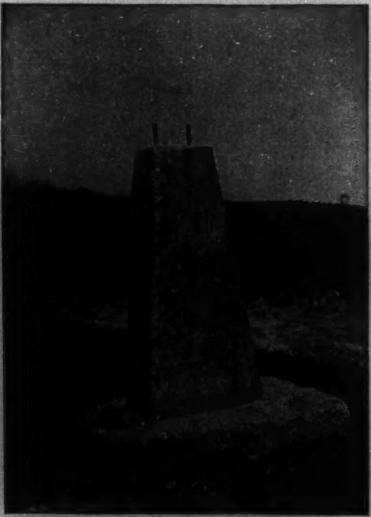

Fig. 18—Tower foundation dug up for purpose of relocation

secured to the poles by braces. On each end of each pair of poles was spiked a box, built up of planking and filled with stone, in order to give sufficient weight to take the uplift due to any pull at the top of the tower. This structure, while far from beautiful, has, so far, proved very satisfactory. The tower construction and the A-frame construction in swamps are shown in the illustrations.

It will be noted that, in some of the illustrations of the towers and A-frames, there is shown a horn attached to a cap on the top of the insulator and another horn alongside of it fastened to the structure and extending some distance above the insulator. This comprises a combined line-structure lightning-arrester, or spark-gap, and lightning-rod. It has been decided to make a careful trial of this method of protection of the line before resorting to a grounded cable; partly because of the great expense of the grounded cable, and partly because there is no reason to think, so far, that it will necessarily afford complete protection in every case. For the present, these line-

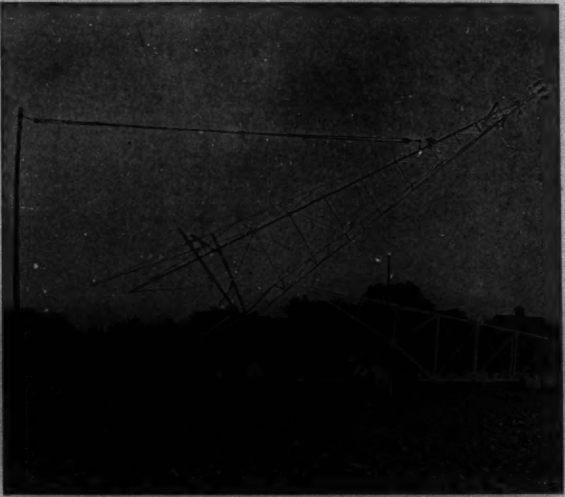

FIG. 19—Erecting 75-foot tower (1)

structure lightning-arresters will be installed only on the top cable, in view of the fact that during the last lightning season, in the course of which a number of insulators were broken by lightning, more than three-fourths of the insulators so broken were top insulators.

The insulator used on all the main-line construction is one especially designed for this plant by the writer. It has probably the greatest factor of safety as regards flashing, etc., of any insulator in practical use to-day, and is considerably larger and heavier than any insulator of which corresponding use has heretofore been made. It consists of three shells nesting in one another and cemented together by means of neat Portland cement, the whole insulator being cemented in a similar manner to a steel pin before attachment to the tower. The insulator is clearly shown in one of the illustrations. The total height

FIG. 20—Erecting 75-foot tower (2)

of it from the edge of the lower petticoat to the top of the head is 19 inches. The diameter of the upper petticoat is 14.5 inches. The insulator used on some of the branch lines is smaller and less expensive than that for the main line, partly because the branch lines receive in general a somewhat lower voltage than the main line and partly because the lines, carrying the small amounts of power they do, are not considered to be entitled to the same insurance as the main line. Each branch line has in series with it, at the point where it is tapped off the main line, 60,000-volt outdoor fuses to cut out the line in case of trouble on it. The fuses consist of lengths of thin copper wire 16 feet long, run through an ordinary small rubber bathroom hose and laid in clips on top of a wooden bar supported at each end and at the center by line insulators mounted on poles.

FIG. 21—The making of a joint (1)

The fuses are parallel to each other in the same horizontal plane, and the distance from center to center is about 25 feet. These fuses have so far proved very satisfactory but will probably in time be replaced with fuses of the explosion type. The outdoor 60,000-volt fuses are shown in one of the illustrations.

There are only three sizes of cables used on the main transmission line, designated by the company as 3/3, 2/3, and 1/3 respectively. The 3/3 cable is aluminum cable, consisting of 19 strands, and having a total area of 642,800 cir. mils, being equivalent to 400,000 cir. mils copper. The areas of cross-section of the other cables are respectively two-thirds and one-third that of the large one.

FIG. 22—The making of a joint (2)

In ordinary straight-away work, the cable lies in the top groove of the insulator, and the pull of the cable is taken care of by means of two aluminum wire ties around the neck of the insulator. One of these ties extends each way along the cable. The tie itself consists of a single loop around the neck of the insulator, the two ends of the loop being twisted around the line cable. The result is that the cable is not really fastened to the insulator at all, but simply lies in the top groove. The ties do not, therefore, perform any function, except when there is a pull on the cable tending to slide it in the direction of its length. The advantages of such a tie are twofold: first, the full strength of the tie wire is developed, which is not the case if a tie is twisted or "pig-tailed," since in such case the tendency is for the tie to cut itself in two at the twist; secondly, the tie does not damage the soft aluminum cable, as would be the case with most of the other ties usually employed.

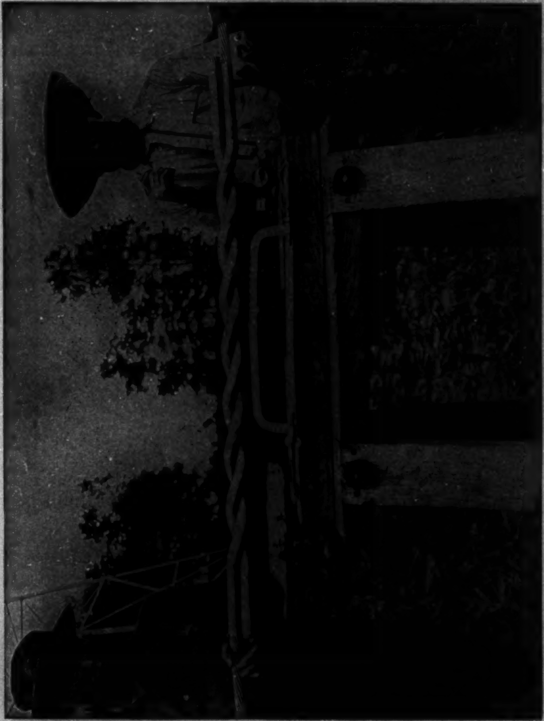

FIG. 23—The making of a joint (3), joint complete

In other than straight-away work, and where it is desirable that the method of fastening to the insulator shall be such as will withstand a pull equal to the full strength of the cable, in case the cable should break, the tie mentioned above is not used, but instead there is employed a cable-clamp and a yoke extending each way on the cable.

In every case the cable near the insulator is protected from possible arcs, so that in the event of an arc there will be a chance

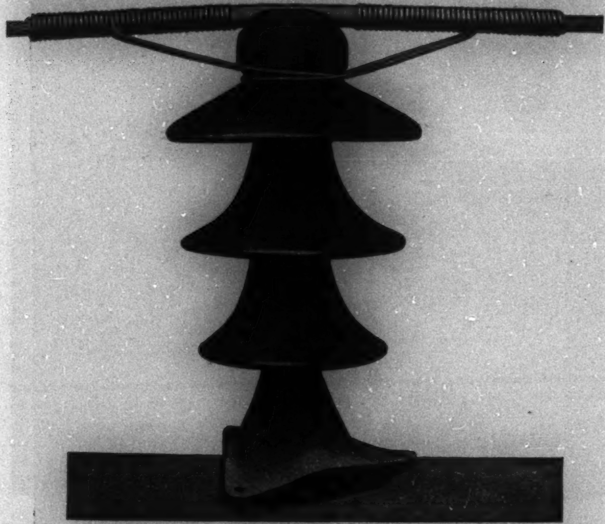

FIG. 24—60,000-volt main-line insulator with tie and cable protection

for the circuit-breaker at the generating station to open before the cable shall have been burned off. This protection is accomplished in the top groove of the insulator by means of sheet aluminum wrapped around the cable at this point to a thickness of $\frac{1}{8}$ inch, and is accomplished on each side of the head of the insulator to a distance of 12 inches from the head partly by the turns of the tie-wire mentioned above, and partly by an additional serving of tie-wire. Where, in the case of the use of cable-clamps, no tie-wire is used, its absence is made up for by additional serving. The photographs show very clearly the methods of attaching the cables to the insulators and the methods of protecting the cables from arcs.

The ends of the line cables are connected by means of twisted-sleeve joints. The method of making these joints is shown in the illustrations.

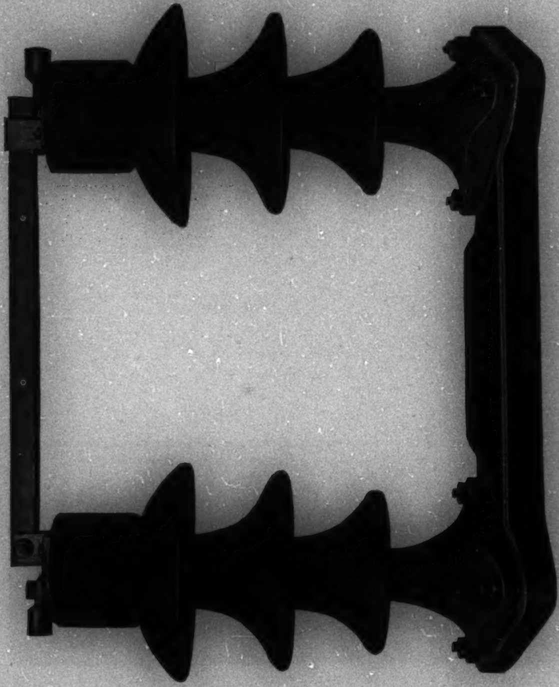

FIG. 25—60,000-volt outdoor line disconnecting switch

At intervals along the line there are provided disconnecting switches for sectioning the line to facilitate testing out in case of trouble, or cutting out any portion of the line which is damaged. There are also provided at certain points, in connection with these disconnecting switches, cross-connecting switches, enabling the interconnection of different portions of the two lines.

On a considerable portion of the company's right-of-way is a wagon road, for use in patrolling the line and delivering material for construction or repair. At certain points along the line there are patrol houses for the storage of material, for taking care of teams, and for the comfortable housing of the patrolmen. Each house has in it a sleeping room, kitchen, and

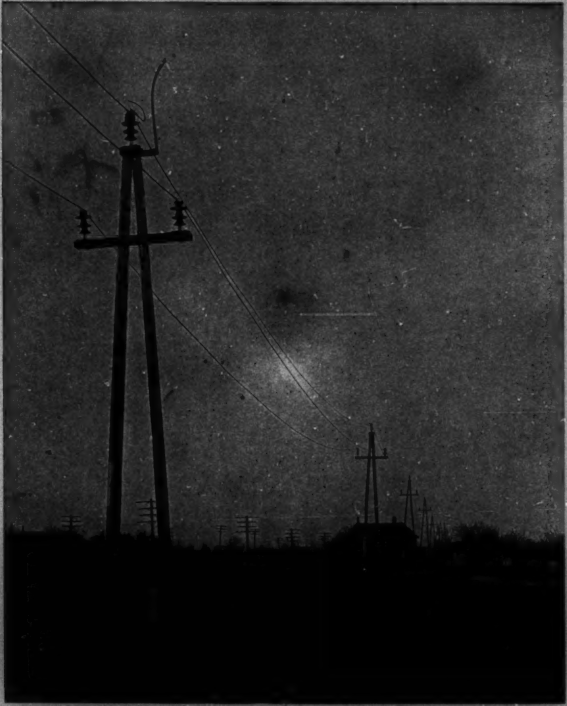

FIG 26—Standard A-frame construction showing line structure lightning-arrester

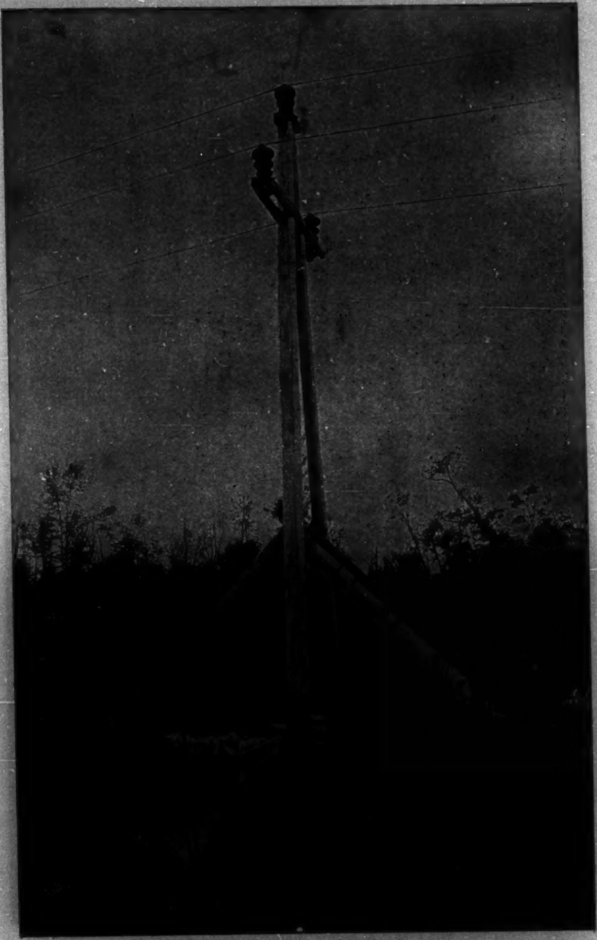

FIG. 27—A-frame construction, Montezuma swamp

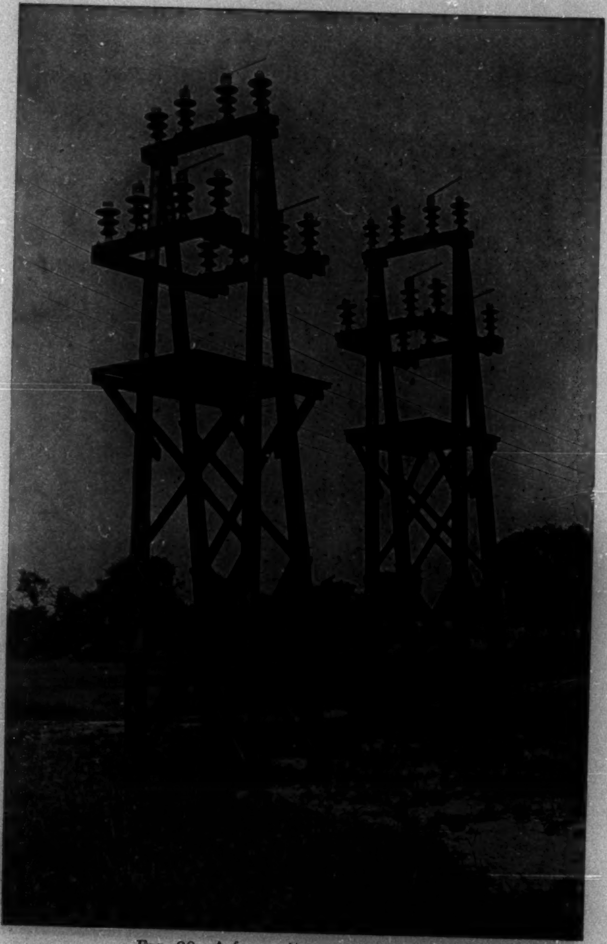

FIG. 28—A-frame disconnecting switches

sitting room. On all of the transmission lines, also, the company has a private telephone line on a separate set of wooden poles. Taps from this line are brought into each of the transmission houses, and in addition to this the line patrolmen have portable telephones which can be connected to the telephone line at any point.

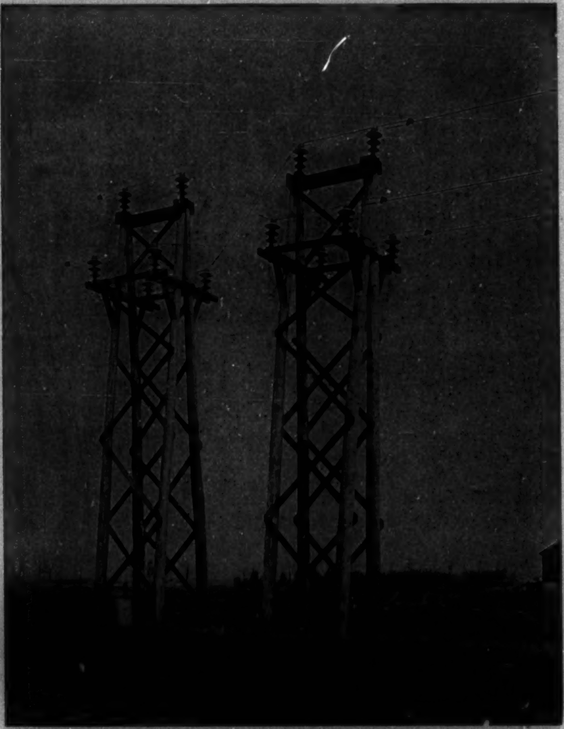

FIG. 29—A-frame transposition

Most of the contracts which the company has for the supply of power cover the delivery of the power at the main-line voltage.

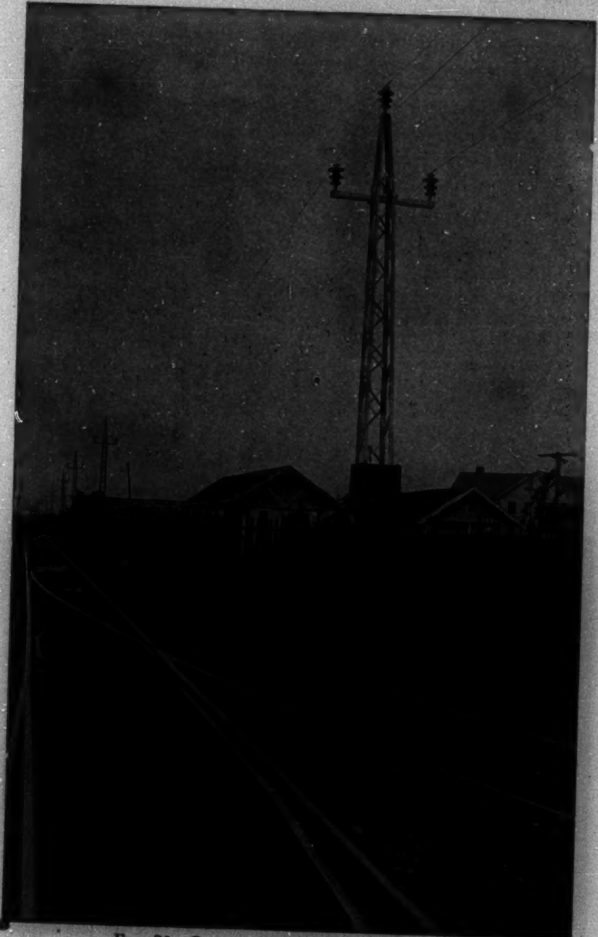

FIG. 80—Galvanized steel poles on railway

Thus far the company has installed only three sub-stations, two of them of considerable size at Lockport and Gardenville, respectively, and one at Baldwinsville, a very small and comparatively inexpensive one. The stations at Lockport and Gardenville have each a normal capacity of 3,000 kw. not including the spare apparatus. They are so designed that their capacity can be indefinitely increased. The Baldwinsville station has a capacity of 750 kw. The station at Lockport has been installed and in operation for some time. That at Gardenville is about complete, but not yet in operation. The accompanying illustrations will, in a general way, make clear the type of construction employed in the Lockport and Gardenville sub-stations; but, as there are a number of features in connection with these sub-stations which are quite different from ordinary

FIG. 31—Lockport sub-station showing 11,000-volt outdoor lightning-arresters

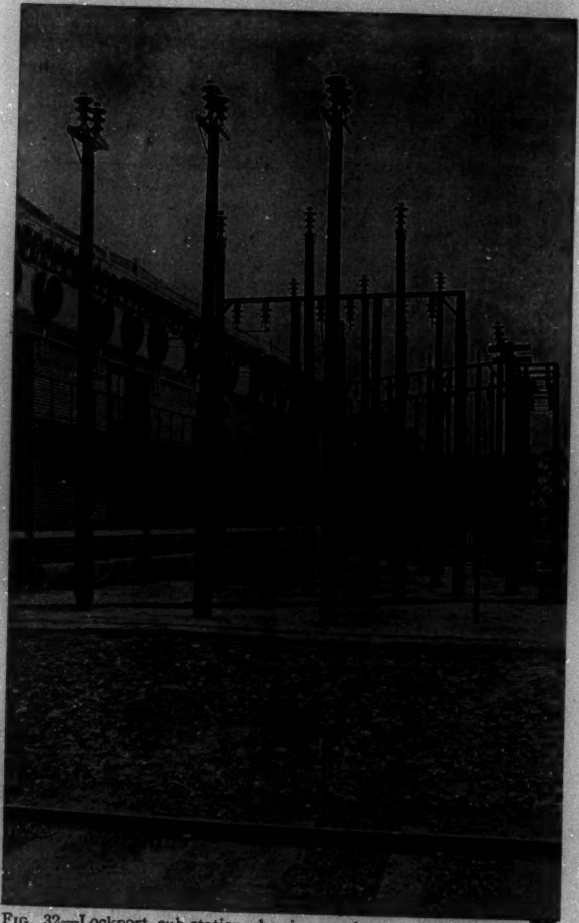

Fig. 32—Lockport sub-station showing outdoor 60,000-volt bus-bars

practice in these matters, a brief description of them will be in order.

The 60,000-volt bus-bars at these sub-stations are outdoors; in other words, these bus-bars have been treated exactly as if they were part of the transmission line and located out of doors in a manner, so far as insulation is concerned, similar to the transmission-line cables. In connection with them are disconnecting switches as shown in the accompanying cut for making various combinations of the apparatus connected to them. Of

Fig. 33—Transformer room, Lockport sub-station

course, the disconnecting switches are not intended to break the working current. When it is necessary to break the circuit under load, it will be accomplished by means of the 60,000-volt electrically operated oil-switches installed in the station which, in the case of the Lockport sub-station, serve also for the control of the two lines to the Buffalo district.

Another feature out of the ordinary in connection with this station is the lightning-arrester equipment. This equipment is also out of doors, and consists of a number of horn-type lightning-arresters mounted on wooden poles in much the same manner as such arresters are ordinarily mounted. The installation differs, however, from the ordinary lightning-arrester installation of this kind, for, instead of there being only one pair of horns for each line conductor, there are three such pairs. One pair is set for a comparatively low striking electromotive

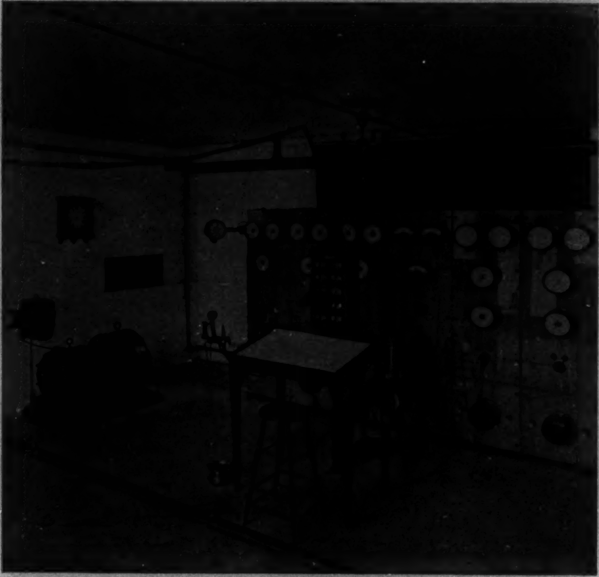

FIG. 34—Switchboard room, Lockport sub-station

force and has in series with it a high resistance; the next pair is set for a higher striking electromotive force, and has in series with it a lower resistance; a third pair is set for very high striking electromotive force and has a fuse in series with it.

The theory on which these arresters are installed is that for ordinary slight static disturbances in the line the arrester having the lower striking electromotive force will discharge, and, since it has in series with it a comparatively high resistance, the resultant disturbance to the system due to the generated current which follows the discharge will be comparatively slight. A more severe static disturbance (whether due to lightning or to any other source), will cause both the arrester having the lowest gap and the arrester having the next higher gap to discharge simultaneously, thus affording two discharge paths to earth, the combined resistance and inductance of which is considerably

Fig. 35—60,000-volt oil-switch and circuit-breaker, electrically operated

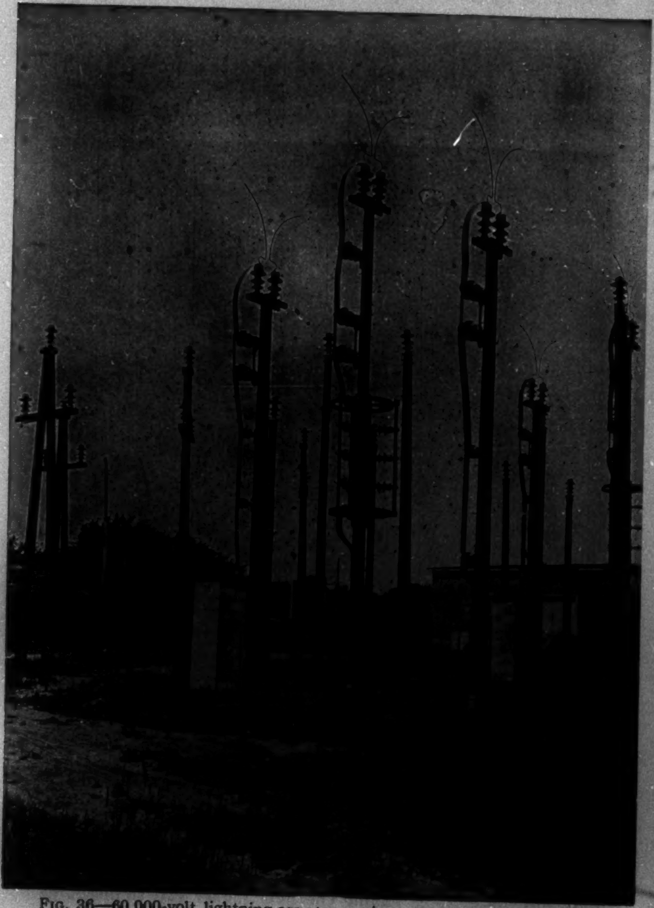

FIG. 36—60,000-volt lightning-arrester equipment; two 3-phase circuits

lower than that of the first path. This will mean a somewhat more severe disturbing effect on the system, due to the generated current which follows. In the case of a very extreme condition; for instance, a direct lightning stroke on the line, the three arresters would discharge simultaneously, the fuse, in the case of the arrester with the highest air-gap, blowing and interrupting the arc upon it, the disturbance of the circuit finally ending upon the other two arresters. Judging from experience in the case of other plants with a much less elaborate arrangement than that outlined, and the experience during the last lightning season with the protection afforded at the Lockport station, the writer believes this method of protection to be entirely effective in the matter of preventing damage to apparatus in the sub-station. Such an installation may, in the case

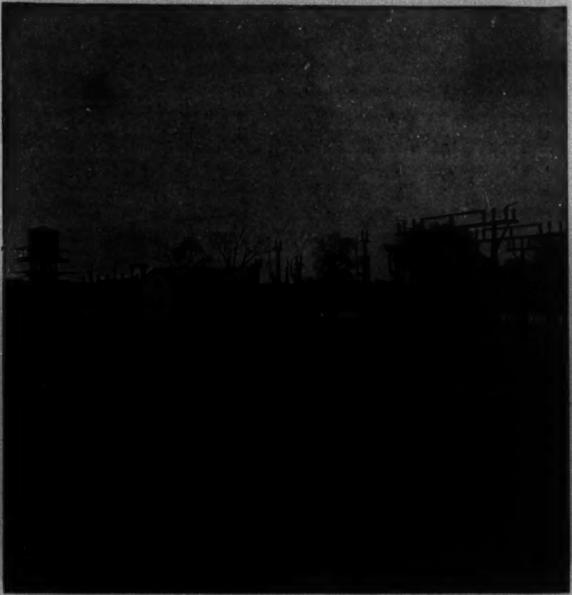

FIG. 37—Baldwinsville sub-station, showing lightning-arresters

of a very severe discharge, such as that due to a direct stroke of lightning, mean a temporary shutdown of the system, or at any rate of the synchronous apparatus operating upon it; but it does not necessarily follow that this will be the case if expulsion fuses be used on the highest gap arrester. Such fuses as have been experimented with in connection with this work operated very satisfactorily. It may be noted in passing that a lightning-arrester equipment similar to that just described for sub-stations is installed also at each point where a branch line is taken off at the main line.

FIG. 38—Typical patrol house

The other features of this station are very similar to those usually found in such installations. There is a complete system of oil piping for putting oil into or removing it from the transformers and oil-switches, and also for storing oil to replace that in the transformers and switches when it may become necessary. There is also provided outside of the building an oil-storage tank for storing oil that has been damaged until such time as it is convenient to put it through the oil-cleaning apparatus. In view of the fact that there is no other continuous water supply available at this sub-station, it has been necessary to drill wells for the supply of water for cooling the transformers. In connection with these wells there has been installed a pumping plant, a water tower, and a cooling pond, the latter for use in case the wells should not be able continuously to supply all the water required.

There will be installed shortly on the company's system two switching stations, one at Mortimer and one at Syracuse. The one at Syracuse will be for taking care of the two incoming 10,000-h.p. lines and the outgoing lines to the consumers in Syracuse. The one at Mortimer will be for taking care of the two incoming 20,000-h.p. lines and five outgoing lines; two of them being a line in duplicate to Rochester; two of them the line in duplicate to Syracuse; and one the Avon branch line supplying several installations, amongst them the station of the Erie Railroad Company, operating their trolley line between Rochester and Avon. Both these switching stations will be equipped with the 60,000-volt electrically operated oil-switches, reverse relays, and other apparatus necessary for properly manipulating the circuits which they control.

The transmission lines of this company cross the rights-of-way of a number of railway companies, and some difficulty has been had in arriving at a satisfactory arrangement with the railways in regard to these crossings. In general, the attitude of the railways is that of being unduly fearful of the transmission lines, and requiring protective precautions of one kind or another. It is, however, gratifying to note that in every case the railway companies have, on investigation, been so well satisfied with the reliability of the transmission company's type of line construction as to waive the elaborate steel protective bridges which have been insisted upon at times in the past, and in most cases little or no extra precautions have been required.

DISCUSSION ON "THE TRANSMISSION PLANT OF THE "NIAGARA LOCKPORT, AND ONTARIO POWER COMPANY," at NIAGARA FALLS, NEW YORK, JUNE 26, 1907

E. J. Berg: You have a telephone circuit in connection with the power lines?

Ralph D. Mershon: We have a separate telephone line on separate poles on our own right of way.

E. J. Berg: The following observations made in Mexico about a year ago have some bearing on this. A 500-volt direct-current temporary station was furnishing power for lighting a number of buildings on the top of a mountain. The station was located in the valley about 500 ft. below. The lines were strung on high-voltage insulators and were about 22 in. apart. A short time before a thunderstorm, static sparks were seen between these lines. At the time, a number of lamps were burning so that the circuit was closed between the lines within 50 ft. of the spark. Furthermore, these same lines were placed within about 2 in. of each other in the building, yet the spark chose to strike 22 in. in air. A lightning-arrester within 50 ft. of the disturbance would apparently not have taken the discharge.

Ralph D. Mershon: We have line structure lightning-arresters about every 2200 ft. Two or three days ago an insulator was smashed on the tower within 550 ft. of one of these lightning-arresters, set for six inches.

J. W. Fraser: It seems to me that the concrete foundations we are using at the present time are very expensive. We are figuring on a new line, and putting in a sort of button about 2 ft. in diameter, of cast iron, and putting it down about 5.5 feet in the ground. Throughout the Carolinas we have fairly solid earth. I see no reason why this foundation should not be as effective, and it does not cost as much as concrete.

Ralph D. Mershon: Mr. Scholes has figured on metallic foundations and anchorages two or three times, and each time the cost of metallic foundation is more than the concrete.

J. W. Fraser: They are using buttons 18 in. in diameter, that weigh 106 lb. in the West. I understand that they are perfectly satisfactory.

F. B. H. Paine: The towers used in the West are in places where they are not subject to sleet or any of the enormous strains our lines are subjected to in this part of the country. It is reasonable to suppose that they can adopt the metallic foundation, as they can use a lighter tower than we can.

Ralph D. Mershon: Under the assumptions made for the towers of the Niagara, Lockport and Ontario Power Co., the resultant of the horizontal and vertical component forces is 15,000 lb. Under test, the towers must stand twice that.

J. W. Fraser: Wouldn't it be as satisfactory to make a lighter tower and use one strong tower every mile?

Ralph D. Mershon: These towers would not stand the condition of breakage of all the cables. Every two miles we have a guyed tower that will stop all breakages that occur; that is, under the conditions of sleet and wind. Mr. Paine can tell you something about sleet on telephone wires.

F. H. B. Paine: A couple of years ago Mr. Hammond V. Hayes was good enough to relieve my mind of the thought that Mr. Mershon had provided too great strength in our lines. He showed me some plaster casts of wires coated with sleet, which had been subject to a wind, according to the United States Weather Bureau, of 100 miles an hour, the sleet and wind occurring at the same time. That was on telephone wire, and the construction came down. The three or four samples I have in mind, which he showed me, were either from western Massachusetts or along the Hudson valley, in that section, and they occurred during the two famous blizzards.

Ralph D. Mershon: No two engineers will agree on the subject of sleet and wind. If an electrical engineer who has not done much in the way of designing framed structures, designs a line in accordance with his ideas of the wind he will encounter, and submits his designs to a bridge engineer, the bridge engineer will probably say that the assumptions and factors of safety are entirely too low. The factors of safety and assumptions for our structures have been criticized for being too low and for being too high, but I believe we are very close to being right.

J. W. Fraser: I do not think it advisable to provide against abnormal conditions.

Ralph D. Mershon: It depends on the amount of power; a small amount of power is not entitled to the amount of insurance that a large amount of power is entitled to. If there is 30,000 h.p. going over a circuit, there is more depending on the 30,000 h.p. than there would be with 5,000 h.p. You are justified in taking more risk in connection with a 5,000 h.p. line than you are with a 30,000 h.p. line. The latter serves a much greater territory than the 5,000 h.p. and industries and utilities which in the aggregate amount to a great deal more than in the case of a 5,000 h.p. service.

J. W. Fraser: We decided that the largest amount of power we could carry over one line normally would be about 6,000 kw. Of course that makes a lighter line.

Ralph D. Mershon: Our conductors starting out over the river are larger than they are farther along the line. The cable is 0.9 in in diameter; add 0.5 in. of ice and it becomes a good size conductor.

In regard to the question of wind pressure, I would confirm something Mr. Buck said this morning in regard to long spans. When we were crossing the Niagara River we had extended over the river a light rope used as a messenger rope. It responded of course to every impulse of the wind. I have observed this rope with the wind blowing pretty hard, and its average position scarcely changed at all, but the positions of different portions of the rope varied over wide ranges. You could see waves running back and forth over it, showing heavy gusts of wind in one place, and gusts of wind of lower velocity somewhere else. The behavior of the rope confirmed the results of the tests made on the Forth bridge, that there is a great difference between maximum and mean wind pressure, and that the maximum average wind pressure on a small area will be much higher than on an extended area.

J. W. Fraser (by letter): Recently we have had a test made on the holding-down power of metallic anchors and the attached curves have been calculated from data obtained. Mr. Mershon says that "The resultant of the horizontal and vertical component stresses is, I think, 13,500 lb." If this is the stress at a point 40 ft. from ground, and the base of tower is 15 ft., each anchor would have to withstand a pull of 18,000 lb. Referring to curve B, two 10-in. channels 2 ft. long, spaced 26 in. on centers, would have to be sunk 6.5 ft. in the ground. The extra cost of these anchors per tower would exceed the cost of ordinary anchors by about $18.00. I take it that Mr. Mershon was referring to the extra strong towers spaced two miles apart, and if I am correct much smaller anchors would be ample for the ordinary towers.

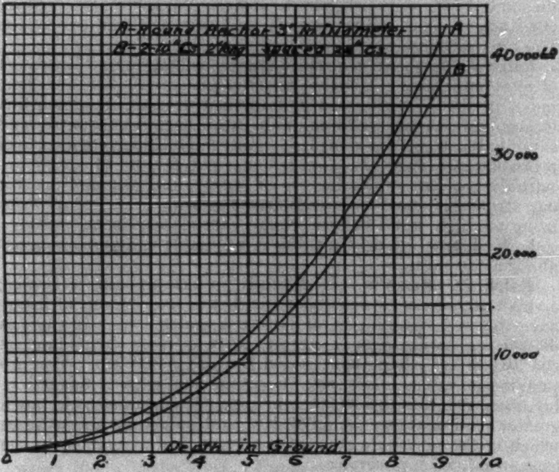

FIG. 1.

It is not only that stone, water, and cement have to be hauled long distances by teams, but the work is delayed excessively, waiting for either the water or the cement or for the foreman to adjust template and set the anchors. In all our line construction we are obliged to provide camping outfits and board for our men, and the delay caused means a great deal more money than the paper estimates of the construction of steel lines.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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LOCATION OF BROKEN INSULATORS AND OTHER TRANSMISSION LINE TROUBLES.

BY L. C. NICHOLSON

Injury to a single insulator, under certain conditions of operation, renders an entire transmission line, many miles in length, entirely inoperative until the faulty insulator be discovered and replaced. The longer the line the more difficult it becomes to find a broken insulator, or to locate other irregularities in operating conditions, and a correspondingly long time is consumed in restoring the line to service.

When long lines are sectionalized by disconnecting-switches spaced at regular intervals, it is possible, by successive applications of voltage to section after section, to determine the particular section which contains the fault, and then to locate the exact point of failure by patroling a considerable length of line. This process is tedious on account of the necessity of manipulating the line-switches upon telephonic advice from the generating station, and by reason of the time required to patrol the particular section containing the fault. For these reasons it is desirable to employ some method of locating faults by means of electrical measurements which shall be capable of a reasonable degree of accuracy, and of being performed in a short time.

There are several well-known methods of locating faults electrically; among these are the Varley and Murray loop tests. These and other ordinary methods operate with low-voltage direct current acting upon a Wheatstone bridge arrangement of resistances and galvonometer, and are readily applied to metallic circuits suffering from a total grounding or short-circuit. If, however, the fault be a partial one, such for instance as occurs on a high-voltage transmission system when an insulator becomes defective by puncture, or otherwise, it is impracticable to apply any of these methods, since a high voltage must act to develop any current-flow under these conditions. It is manifestly impracticable to manipulate adjustable resistances quickly and accurately in a high-voltage circuit, or to use direct-current instruments such as a galvonometer, because alternating current is demanded by the relatively high voltage which it is necessary to employ. It will be appreciated that, for a fault-locating method to be trustworthy, it must be adapted to the normal operating potential of the transmission line, inasmuch as partial faults sometimes develop which will withstand normal voltage for a short time. It is therefore essential and also desirable to employ the generating, transforming, and switchboard apparatus of the generating station for making fault-location tests upon the transmission lines. A simple scheme of connections involving the manipulation of a few hook-switches has been employed for this purpose upon a long-distance high-voltage circuit, and it has been found possible to locate quickly and accurately any fault seriously interfering with operation.

The particular plant upon which such a test has been operated transmits power at 60,000 volts, 25 cycles, three phase, over lines approximately 160 miles long. The line conductors are of aluminum, spaced seven feet apart, and are carried partly on steel towers and partly on wooden structures. In both cases the insulators are supported on electrically grounded steel pins, a ground-wire being used for this purpose on the wooden structures. The step-up sending transformers operate delta-star with neutral grounded. Under these conditions of operation and line construction, it is evident that an insulator becoming disabled flashes and holds an arc between the line conductor and the insulator pin, which constitutes a short-circuit on one of the transformers and prohibits further service until the injured insulator be replaced. Causes other than broken insulators may interfere with operation; for example, branches of trees fouling wires during wind storms, or even malicious interference. However, trouble necessarily appears from one wire to earth, or from wire to wire.

The method of locating faults referred to above, consists in supplying current from a generator and transformer to the fault to earth through a divided circuit or a loop, formed by joining two line conductors together at both ends, one of the wires so connected containing the broken insulator to be located. The total current supplied divides quantitatively between the branches of the loop in a proportion depending upon the ratio of the two impedances to the fault which ratio is determined by, and therefore is determnative of, the location of the fault. Indicating ammeters or integrating wattmeters connected in the two branches of the loop by means of proper transformers show the current or power supplied through the respective conductors. Amperes or watts so measured, together with the known electrical constants of the line under test, serve to determine the geographical location of the fault. Evidently, only the relative currents flowing in the two paths at the same instant, or the relative integrated power delivered during any length of time, need be ascertained.

Fig. 1 shows the scheme of connections which has been employed. The loop consists of wires *A* and *B* which have a metallic short circuit placed on them at the generating station just inside the current transformers, and a similar one at the receiving station just outside the disconnecting switches. It is, of course, necessary for the generating station operator to order a short circuit placed on the proper wires at the distant end of the line when a test is to be made. *E* is the high-tension winding of a power transformer. Its connection to earth is through the neutral which operates grounded. The particular transformer used will depend upon which wire is in distress. *R* is a limiting resistance connected in series with the loop, and is designed to limit the total flow of current to the capacity of the transformer and the measuring instruments. At *V* is represented a fault to earth, which usually takes the form of a broken insulator, over the surface of which current flows through an

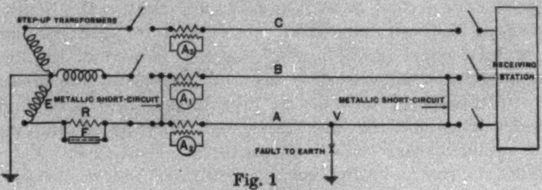

Fig. 1
SCHEME OF CONNECTIONS.

arc. A_1, A_2, A_3 represent indicating ammeters in the secondaries of current transformers.

The limiting resistance *R* may be connected in either the high- or low-tension side of the transformer. The amount of resistance used, depends largely upon the character of the fault to be located. It must be large enough properly to limit the current flow, and must not be so high that it will interfere with a continuous flow of current through an arc after the fault has developed. Moreover, when testing for a fault which will resist nearly normal voltage on a long transmission line taking a large charging current, there occurs a loss of potential across this resistance on account of the charging current flowing through it, so that the potential operating upon the fault may be less than normal potential of the system and too low to flash over the injured insulator. To obviate the necessity, under such conditions of raising the voltage of the system above normal, an expulsion fuse, *F*, shunting this limiting resistance has been employed. The capacity of this fuse must be at least equal to the normal charging current of the line. Its use ensures full voltage at the fault and allows the current flow to be properly controlled by the resistance *R* after the fault has developed and the fuse has burned. Any automatic overload circuit-breaker could be substituted for the fuse.

Since the resistance drop is in quadrature with the condensance voltage, a fuse or its equivalent is necessary only when testing long lines, and then very rarely.

A cheap and entirely satisfactory form of resistance, well adapted to use in the high-tension circuit, consists of ordinary cement concrete columns supplied with expanded-metal terminals. Four columns, 12 ft. long, a square foot in section, each having a resistance cold of about 2000 ohms, have been used in multiple or singly as occasion demanded. The temperature-resistance coefficient of concrete being large and negative, it is an easy matter to arrive at a proper resistance by heating the columns with current. Such flexibility in this resistance has at times proved very convenient.

Experience so far obtained, indicates that, in a large majority of insulator failures, a 1,000-ohm concrete resistance in the high-tension side does not prevent flashing of a broken insulator, nor does it interfere with satisfactory current readings. Occasions do arise when the fuse is necessary, and when a comparatively low resistance must be used to maintain an arc at the fault long enough to obtain current readings on indicating ammeters. It appears that after an arc has once been established it will hold indefinitely, provided the current flow be not too restricted. The more incomplete the fault and the longer the striking distance, the larger the current required. From 50 to 100 amperes has proved an appropriate range of current for general testing purposes. Variations that occur when using this amount of current are usually gradual—being due to decreasing resistance of the concrete—so that there is rarely any difficulty experienced in obtaining satisfactory simultaneous ammeter readings during a period of, say, five or ten seconds.

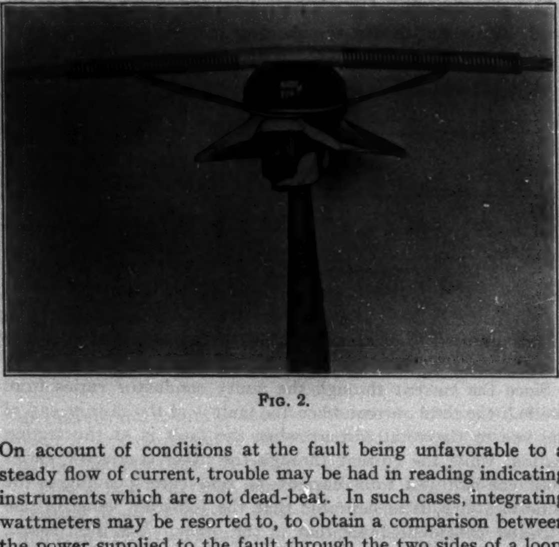

FIG. 2.

On account of conditions at the fault being unfavorable to a steady flow of current, trouble may be had in reading indicating instruments which are not dead-beat. In such cases, integrating wattmeters may be resorted to, to obtain a comparison between the power supplied to the fault through the two sides of a loop. Only in extreme cases, such for example as disturbances caused by swinging tie-wires or tree branches, is it necessary to use wattmeters.

Fig. 2 shows an insulator broken by a stone in such manner that it withstood operating potential for a few seconds, the striking distance being about seven inches. This insulator was located easily with ammeters which were not dead-beat.

The effect of an arc upon the cable is an important consideration. If it is burned so as to require splicing, considerably more time is consumed in restoring the line to service than if only a broken insulator is to be replaced. This is particularly true with long spans, on account of the weight of the cable to be handled. Under ordinary operating conditions, it is impossible to know how much the cable is burned by the short-circuit current at breakdown and how much by the testing current. Damage to the cable by an arc carrying 100 amperes sustained forty seconds has been found to be insignificant when the striking distance is several inches. It appears that there is some damage if the arc is short and confined, such as would obtain in the case of an insulator punctured through the head. However, during the short period required to read the instruments, the cable does not suffer materially. Where shields are used to protect the cable, there is no damage in any event.

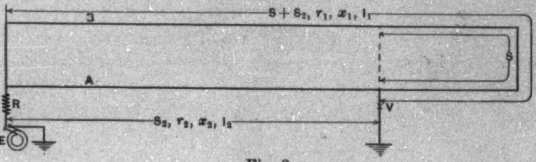

Fig. 3

Since the current through the faulty conductor varies from one half the total current when the fault is at the distant end of the line to the total current when the fault is at the testing station, while the current through the other conductor varies from one-half the total current to zero corresponding to the same locations, it is desirable that the full-scale value of one ammeter should be twice that of the other. For this reason, and on account of their superior accuracy, portable instruments are preferable to the switchboard type.

Referring more particularly to the division of current between the two paths, it has been found that this division takes place in accordance with Ohm's law, or that the currents I_1, I_2 are inversely proportional to the ohmic resistances r_1, r_2 of the two branches.

Assuming the resistance volts of the two branches equal, it is interesting to note how reactance volts are also equal. The two parallel wires constituting the loop, Fig. 3, carry currents in the same direction to the fault, and in opposite directions beyond it. These currents, I_1, I_2, are of the same phase and frequency but of different magnitude, I_2 being larger than I_1. Only that magnetic flux included between the wires need be considered as influencing a division of current, inasmuch as the flux which embraces both wires affects only the total impedance of the entire circuit. The flux included between the wires up to the fault is the resultant of two oppositely acting magnetomotive forces separated in space by the distance between centers of wires. The flux density at any point within either wire is proportional to the current and to the distance from the center, while at any outside point it is proportional to the current but inversely proportional to the distance from the center.

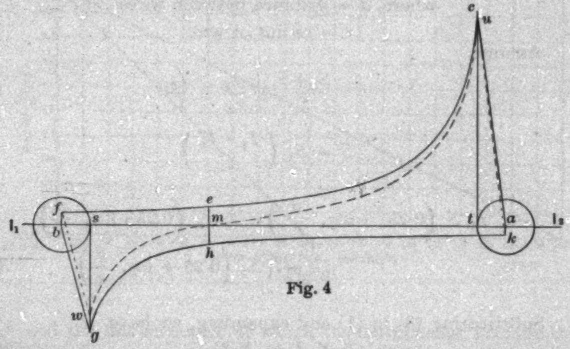

Fig. 4

Fig. 4 is a graphical representation of magnetic conditions existing at any instant. Area *a c f b* represents flux due to I_2 and area *b g k a* that due to I_1, I_2 being in this case twice as large as I_1. At *m*, a point situated so that $\frac{am}{bm} = \frac{I_2}{I_1}$, there is a complete cancellation of magnetomotive forces. If the two currents are in phase, this point remains one of zero flux, and the resultant flux on either side of it caused by the difference between the two magnetomotive forces is that influencing the current flow in the corresponding wires. This resultant, represented by the dotted line *k u m w f*, obtains through a distance S_2, Fig. 3, while the flux in the loop beyond the fault, represented by the area *b g k a*, obtains through a distance S.

So that,

$$\frac{X_2 I_2}{X_1 I_1} = \frac{I_2 S_2 \left(0.25 + \log_e \frac{d}{r} \; \frac{I_2}{I_1+I_2}\right) - I_1 S_2 \log_e \frac{I_1+I_2}{I_1}}{I_1 S_2 \left(0.25 + \log_e \frac{d}{r} \; \frac{I_1}{I_1+I_2}\right) - I_2 S_2 \log_e \frac{I_1 I_2}{I_2} + I_1 S \left(0.25 + \log_e \frac{d}{r}\right)} \qquad (1)$$

where, d = distance between wires
r = radius of wire

Assume,

$$\frac{S_2+S}{S_2} = \frac{r_1}{r_2} = \frac{I_2}{I_1} \qquad (2)$$

$$S = S_2 \left(\frac{I_2 - I_1}{I_1}\right)$$

$$I_1 S \left(0.25 + \log_e \frac{d}{r}\right) = I_2 S_2 \left(0.25 + \log_e \frac{d}{r}\right) - I_1 S_2 \left(0.25 + \log_e \frac{d}{r}\right) \qquad (3)$$

Substituting (3) in (1) and expanding, we have,

$$X_2 I_2 = X_1 I_1$$

or the inductance drop is the same over each path. Since the total volts are identical, this result follows directly from equation (2), as does also the assumption that the two currents are in phase.

From a consideration of resistance only,

$$\frac{I_2 - I_1}{I_2 + I_1} = \frac{\frac{r_1 - r_2}{2}}{\frac{r_1 + r_2}{2}} = \frac{\text{ohms from fault to distant end of line}}{\text{total resistance of one wire}} \qquad (4)$$

Either (2) or (4) may be used to compute fault locations. The latter is less influenced by observation or instrument errors and lends itself more readily to graphic representation. If line-structure numbers of a given circuit and the ratio $\frac{I_2-I_1}{I_2+I_1}$ be used as coordinates, a chart may be constructed, as Fig. 5, from which the fault location may be readily taken. This chart contains right lines drawn from the point $\frac{I_2-I_1}{I_2+I_1} = 1.00$ to the line-structure number at which the loop is closed. The use of such a chart makes it possible to test to any point along the line at which it may be convenient or desirable to place a short circuit, without the inconvenience of computing the resistance to that point. Such flexibility and ease of construction is not true of a chart based upon the relation between $\frac{I_2}{I_1}$ and the line structure at which the fault occurs, because this relation is hyperbolic.

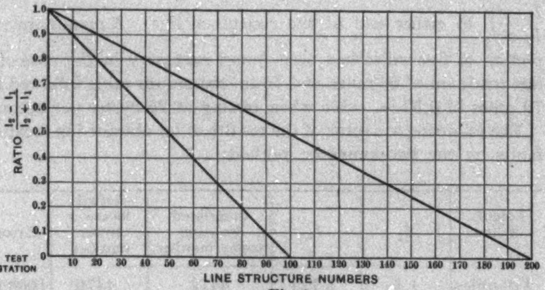

Fig. 5

When testing lines whose conductors are not of uniform cross-section throughout, the foregoing method is not applicable without modification. Whether large wires be followed by small ones, or the reverse, the current flow will not be determined by resistance only. If the wires are larger near the testing station than farther out, the effect is to locate the fault too far away; to locate it too near if small wires be followed by large ones. The reason for this is evident from a consideration of the relative impedance of the two branches of the loop. The branch having the larger ratio of inductance to resistance, of course takes relatively less current than that indicated by resistance. A comparison of inductances is rendered complex on account of the phase-displacement which takes place between the two currents by reason of the disparity between the ratios of inductance and resistance.

The error involved through considering resistance only is, however, a linear function of the distance from the distant end of the line to the fault, if it be in the region beyond the junction of the two sizes of the cable, and likewise of the distance from the testing station if the fault be nearer than the junction point. Thus it is possible, by making a single test upon a fault placed at the junction of the two sizes of wire, to obtain a correction which is applicable to the entire line. This correction is readily applied to the graphic chart mentioned above. It consists of right lines drawn from the experimentally determined value of $\frac{I_2 - I_1}{I_2 + I_1}$ to either end of the resistance line. A maximum correction of five miles has been found necessary in the case of a line made up of 60 miles of 0.75-in. aluminum cable followed by 70 miles of 0.52-in. cable when testing at 25 cycles per second.

The following are some of the results so far obtained in locating faults by the two-ammeter method:

Length of line	I_1	I_2	Computed location tower number	Actual location tower number	Error
118 miles	1.1	1.125	4472	4479	1000 ft.
118 "	1.53	1.55	4482	4481	200 "
36 "	1.56	2.4	512	513	500 "
23 "	0.4	4.5	151	153	1000 "
60 "	1.36	3.57	512	513	500 "
60 "	0.8	2.00	520	519	500 "
60 "	1.70	2.05	730	731	200 "

This list includes a variety of insulator failures. Some of them were complete grounds, while others withstood high voltage. In only one case was there any trouble in obtaining satisfactory ammeter readings—this being a loose wire swinging in a wind storm.

The time consumed by an experienced operator in making a test under ordinary conditions is about thirty minutes There is sometimes a delay on account of the necessity of communicating with the distant end of the line.

The test is subject to the following restrictions: when several faults are on a single wire, they must be located in reverse order of their insulating values and must be repaired in the order located; when all three wires are in trouble, the one having the highest insulation cannot be tested until one of the others is repaired; if two complete grounds a considerable distance apart occur on a single wire, the localizaton will be in serious error.

These conditions are for the most part exceptional, although entirely possible. None of them has presented itself since this method of testing has been in use.

Discussion on "Location of Broken Insulators and Other Transmission Line Troubles," at Niagara Falls, N. Y. June 26, 1907

L. T. Robinson: It seems to me that the method proposed is open to some serious limitations, and that the good results obtained are chiefly on account of the experience of the people who have handled it. For instance, in the table, in the first example given, an error of 1% in the determination of either I_1 or I_2 will make the result practically 2,000 ft. instead of 1,000 ft.

Ralph D. Mershon: I understand that this break, 1760 ft. from the station was located in three-quarters of an hour by an ordinary station attendant. One-third of a mile is a small portion of 100 miles.

L. T. Robinson: I was about to say that the thing involved is the determination of the ratio between I_2+I_1 and I_2-I_1. It would seem impossible to develop the method further and get much greater accuracy. An instrument could be made having two windings carrying I_2 and I_1 in opposite directions that would measure I_2-I_1 directly, and another instrument with two windings carrying I_2 and I_1 in the same direction which would measure I_2+I_1, and these could be combined into one instrument that would determine the ratio of the two quantities directly. This would be an instrument without spring control at all.

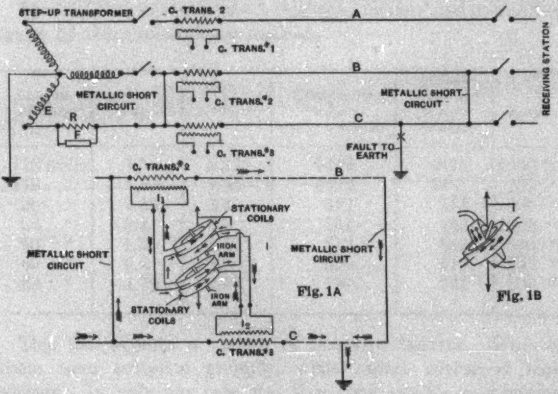
STEP-UP TRANSFORMER
C. TRANS. 2
A
C. TRANS.#1
B
RECEIVING STATION
METALLIC SHORT CIRCUIT
C. TRANS.#2
METALLIC SHORT CIRCUIT
E
R
C
F
C. TRANS.#3
FAULT TO EARTH
C. TRANS.#2
B
I1
STATIONARY COILS
IRON ARM
METALLIC SHORT CIRCUIT
METALLIC SHORT CIRCUIT
Fig. 1A
Fig. 1B
IRON ARM
STATIONARY COILS
I2
C
C. TRANS.#3

Fig. 1

In Fig. 1 I show such an instrument connected to a circuit in the same way that the ammeters are connected in Fig. 1, of the paper. In that part of the sketch lettered Fig. 1A the compound windings are shown acting on two separate iron vanes, mechanically connected, and in 1B both the compound windings act on the same iron vane.

Ralph D. Mershon: You would make these windings affect the same core?

L. T. Robinson: Yes; its action is based on the assumption that the two currents are in phase ordinarily, and that the line resistance, inductance, and capacity are uniformly distributed. An instrument, as described, in which the windings are properly placed, and without spring control, would indicate the ratio between the two values, previously referred to, and its indications could be directly applied to the chart, Fig. 5.

Ralph D. Mershon: These instrument coils would have to be so arranged that they would have comparatively little effect on the circuits that feed them.

L. T. Robinson: The elements of the instruments would be connected to the lines through current transformers, and would have no more effect than any ordinary instrument. Being a ratio instrument, it would simply be the torque that would fluctuate for variations in the currents used, and not the torque ratio. It would be an instrument similar to a power-factor indicator or to a frequency indicator.

F. B. H. Paine: I think Mr. Nicholson has given a good deal of consideration to the various means of improving the details. The purpose of the paper is to indicate the possibility of what can be done with the ordinary commercial things he had about him, and to help us in determining faults and enabling us to correct them quickly. He has not quit thinking about the matter. Mr. Robinson's comments simply reenforce the importance of that.

L. T. Robinson (by letter): To the above I would like to add that since this discussion took place it has been pointed out to me that a much simpler instrument, embodying the same general principles, but in which there are only two simple windings, one carrying I and the other I_2, instead of the two compound windings, referred to above, would be satisfactory. This is obviously true and would simplify the instrument without rendering it less useful.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 26, 1907.

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SWITCHBOARD PRACTICE FOR VOLTAGES OF 60,000 AND UPWARDS

BY STEPHEN Q. HAYES

The idea of this paper is to touch briefly on the salient points of interest in connection with high-voltage switching practice and if possible to bring out in the discussion the opinions of various engineers interested in this line of work, relative to such points as have not been definitely settled by standard practice as being the best solution of the problem.

The reason for limiting this paper to voltages of 60.000 and upwards is that, while the design of stations for voltages up to 60,000 has often been described, but little has been written regarding any for higher pressures. It might be remarked, however, that the switchboard practice for these higher pressures does not differ very materially from that found desirable for voltages from 33,000 to 60,000. In fact 33,000 volts seems to be the critical point at which it is found advisable to change the type of switching devices, wiring, etc., and most of the remarks in this paper would apply for any installation above 33,000 volts.

In comparing the merits of different types of apparatus, the relative advantages and disadvantages of the conflicting designs have been stated in a manner as free from bias as possible, but the statements are of course the personal opinions of the writer and consequently are open to criticism from others having a different point of view.

The matter of suitable switchboard equipment for any plant may be briefly summarized as follows:

I. *General Scheme of Connections.* Under this heading it is necessary briefly to consider the following matters:

a. Type of plant.

b. Frequency.
c. Transformers.
d. Flexibility versus simplicity.
e. Main connections.

II. *Necessary equipment.* Under this heading should be weighed the relative advantages of the following:

a. Switchboards, panel type.
b. Switchboards, pedestal type.
c. Switchboards, desk or bench-board type.
d. Types of oil circuit-breakers.
e. Types of disconnecting-switches.
f. Types of protective apparatus.
g. Bus-bars and wiring enclosed.
h. Bus-bars and wiring open.

III. *Present design.*

a. Typical station for 60,000 volts.
b. Typical station for 100,000 volts.

IV. *Future design.*

a. Indoor transformer and switching stations.
b. Outdoor transformer and switching stations.

I-*a*. *Type of plant.* Without exception, American plants operated at or designed for voltages of 60,000 or higher employ three-phase circuits and obtain the high voltage by means of transformers. For this reason, this is the only type of plant which will be considered in this paper as being of practical interest at present.

I-*b*. *Frequency.* Nearly all the important transmission systems operate at frequencies of 25 or 60 cycles, although frequencies between these limits are used in Mexico and elsewhere, and a lower frequency has been suggested for large railway work. The switching equipment, however, being independent of the frequency, it is unnecessary to consider this matter here.

I-*c*. *Transformers.* For plants of the type considered in this paper the transformers are invariably oil-insulated and usually water-cooled, and may be built either in single-phase or three-phase units and connected in delta or star. With delta connections it is often desirable to cut out any one transformer, leaving the remaining two connected in *V*; knife-switches or oil circuit-breakers are sometimes supplied for this purpose in addition to the other switches or breakers that would normally be used.

With star connections, if the neutral is grounded, it is often feasible to use smaller switches, breakers, etc., owing to the lower insulation strain. By connecting the instrument series transformers at the neutral point instead of in the main leads a cheaper and better arrangement for supplying current to the meters or relays can often be made. The relative advantages of delta or star connections, being a question of transformers and not of switchboards, will not be taken up in this paper.

I-*d*. *Flexibility versus simplicity.* In settling on the design of a power plant, it is necessary for the engineer to consider carefully the relative importance of flexibility and simplicity, and to determine the relative value of apparatus needed only in emergencies and the saving resulting from its omission. While it is possible to duplicate the equipment of switches, bus-bars, etc., so as to take care of almost every contingency, or to reduce the equipment so that trouble in one or two places may seriously cut down the output of the plant, a happy medium can usually be found.

Although the conditions of each plant have to be carefully examined, and due consideration given to the nature of the load, capacity of station both for initial and ultimate installation, sizes of generator and transformer units available; the general problem for all plants is to obtain the maximum amount of flexibility and safety, with the minimum cost of apparatus and building to house the apparatus. This is particularly true with plants for extremely high voltages, and many ingenious and effective schemes have therefore been evolved for reducing the number of high-tension breakers, switches, etc., to a minimum.

I-*e*. *Main connections.* The paper read by Mr. D. B. Rushmore before the annual convention of the Institute in Milwaukee, May, 1906, on the subject of " Electrical Connections for Power Stations," covered the subject so fully that the writer will not devote much space to it here.

The relative advantages of the single bus-bar system, double bus-bar system, the group system, and the ring system are matters for discussion; the particular system decided on is often a matter of local conditions and a compromise between flexibility and cost.

Except where local conditions of low head or some other cause limit the size of the generators, it is usually advisable to have the transformer banks equal to the capacity of one or two generators, and to have the transmission lines of the same capacity as the transformer banks, to permit independent operation of the outgoing feeders with the minimum amount of apparatus and the maximum amount of flexibility. To obtain this flexibility and ready interchange of units, it is necessary in most instances to install a low-tension and a high-tension bus-bar, although occasionally it is feasible to have the generators connect directly to a bank of transformers or to have the transformer bank feed out directly on the line.

II. *Switchboards.* In practically all high-voltage plants of recent design, the high-tension circuits are controlled by electrically operated oil-switches or circuit-breakers. The devices for use with these oil-switches are usually mounted on a switchboard of the (*a*) panel type, (*b*) pedestal type, or (*c*) desk or bench-board type. Occasionally two or more of these types are used in the same station.

The material of the switchboard panels, the top of the control desk, or the face of the pedestal is ordinarily blue Vermont marble or slate with either oil or marine finish. Blue Vermont marble, in the opinion of many people, presents a somewhat finer appearance than the slate, but it has the drawback of showing oil-stains and scratches, and it is hard to obtain a good match for large switchboards. The difficulty of keeping an exact record of the shade and markings of the marble shipped to a certain customer, in case it is desired to supply additional panels or additional desk sections at a later date, militates somewhat against its use.

The slate, whether marine finish or oil finish, has the advantage of presenting a far more uniform shade and a shade which may be duplicated with almost absolute certainty when additions are desired. While it is almost impossible to remove a deep scratch or bad spots from a polished blue Vermont-marble panel, it is a fairly simple matter with oil-finished or marine-finished slate. The oil finished slate panel can be treated with vaseline, while with marine finish, additional paint put on with an atomizer can be used to cover any spots, scratches, or other imperfections. The dull-black finish of the slate, moreover, causes the instruments, controlling devices, etc., to stand out in bold relief and has no tendency to reflect the light in the eyes of the attendant.

II-*a*. *Panel boards.* Where the panel type of board is used, the panels are simply modifications of those required for lower voltages. The usual equipment of instruments for the generators transformers, feeders, etc., are mounted on the same panels as the controlling devices. This type of construction is used where the number of units is comparatively small and the length of the board will not be too great. It is also employed where the space needed for the instruments is so great that any attempt to reduce the length of the operating board by mounting the controlling devices on a desk, or any more compact arrangement, would result in placing the instruments at such a distance from the operator that it will be difficult for him to see their scales and pick out the meters belonging to any one circuit. The plant of the Canadian Niagara Power Company is equipped with this type of panel board.

II-*b*. *Pedestal type*. This type of control is ordinarily used in plants with voltages lower than those referred to in this paper and where the number of generators is small in comparison with the number of feeders. In this case the generators are controlled from pedestals while the feeders are controlled from panels. This system is, however sometimes used for high-voltage plants and was adopted for the distributing station of the Ontario Power Company at Niagara Falls. With these control pedestals, it is customary to furnish posts for the instruments.

II-*c*. *Control desk or bench board*. Where it is desired to reduce the length of the operating board to a minimum, it is customary to install a control desk or bench board and to mount on the top of the desk the various controllers for the circuit-breakers electrically operated field-switches, field rheostats, governor motors, etc. Wherever possible, the instruments for the various circuits are mounted in such a position relative to the sections of the control desk as to indicate clearly to the station operator the instruments belonging to particular circuits.

With a control desk, the instruments may be mounted either on independent switchboard panels, on panels forming the back of the control desk, in an instrument frame back of and usually higher than the top of the control desk or on instrument posts. Where independent panels are used with a control desk the panels usually occupy a greater amount of space than the desk, and it is possible for the station operator to become confused in determining the instruments belonging with a certain generator or feeder whose controlling devices are on the desk. As a rule, card-holders or name-plates are placed both on the desk and in the panels, and the grouping of the instruments is made to correspond as far as possible, with the grouping of the controlling devices.

Where the instrument panels form the back of the control desk, the instruments are arranged to correspond in location with the controlling devices for the same circuits. This is the type of desk used by the Electrical Development Company at Niagara Falls.

A modification of this arrangement permits the station attendant to face the generator room and readily observe the operation of the machine he expects to control. An independent instrument frame is provided back of and above the control desk and its height is such that the operator looks over the top of the desk and under the bottom of the frame.

A control desk 18 ft. long and an instrument frame of the type referred to are shown in Fig. 1, which illustrates the equipment being furnished for the control of six 5000-kw. generators, six banks of 88,000-volt transformers, and four 88,000-volt transmission lines.

In the plant for which the desk shown in Fig. 1 is used, each of the six transformer banks is provided on the high-tension side with an electrically operated oil circuit-breaker and a double set of disconnecting-switches, so that a bank of transformers may be connected to either of the two sets of high-tension bus-bars. These two sets of high-tension bus-bars are divided in the middle, but may be tied together through electrically operated junction circuit-breakers. The two sets of bus-bars on each side of the junction breakers may also be connected by means of electrically operated tie-breakers.

The four outgoing transmission lines are each provided with an electrically operated oil circuit-breaker and a double set of disconnecting-switches, so that the breaker may be connected to either of two sets of bus-bars. With this arrangement it is possible to operate the four transmission lines entirely independently, and a very flexible combination of generators, transformers, and lines may be obtained.

The top of this desk is made of marine-finished slate, while the ends, front, and back are made of planished steel plate, which is light, strong and readily removable to permit access to the interior of the desk. The instrument frame is of steel and the unit idea has been carried out to allow for future extensions.

This desk, like most of those where the connections are at all complicated, is provided with a miniature bus-bar system with the usual red and green lamps to indicate whether a breaker is open or closed. As the double-throw system on the high-tension circuits is obtained by means of disconnecting-switches, miniature disconnecting-switches are placed in the mimic bus-bars. The idea is that the station attendant, after closing or opening any of the high-tension disconnecting-switches, will report the fact to the switchboard operator so that the latter may set the miniature ones to correspond. As the arrangement of the disconnecting-switches is not likely to be changed from day to day, it is believed that this scheme will furnish the operator with

FIG. 1—Control desk for 88,000-volt plant

all necessary information as to the conditions of the high-tension connections.

In this plant the electrical control is extended to the field and exciter circuits as well as to the generators, transformers and lines. All the controllers, etc., are mounted on the top of the desk, the instruments being in the switchboard frame. With the exception of the power-factor meters, where a 360-degree scale was desired, and the synchroscope, where it is necessary for the needle to revolve, all the meters, both alternating current and direct current, are of the same general appearance.

FIG. 2—Switchboard for exciter and field control for 88,000-volt plant.

The motor-operated rheostats and the solenoid-operated switches for the exciters and the field circuits of the generators are arranged to form the panel board shown in Fig. 2.

The four outgoing 88,000-volt lines were each provided with a complete set of graphic recording ammeters, voltmeters, wattmeters, power-factor meters, and frequency meters, as well as polyphase integrating wattmeters.

The control desk for the line and transformer circuits in the receiving station of this plant is very similar to that for the generating station, but some additional refinements are being introduced. Instead of having miniature disconnecting-switches on the desk, small green telephone lamps will be placed in the miniature bus-bar system on the desk. These lamps will be connected in series with a standard incandescent lamp and a snap-switch located in the high-tension room, or in the passage way from which the disconnecting-switches are to be operated. The intention is to have the station attendant, after pulling out the disconnecting-switches, turn on the snap-switch and in this manner light the green lamp on the desk and the standard lamp near the switch. In a similar manner, after closing the disconnecting-switch, the snap-switch is turned to extinguish the light. Failure of the telephone lamps would indicate the danger position; that is, that disconnecting switches were closed.

In this receiving station, as it will be difficult for the attendant in the passage-way near the disconnecting-switches to see whether the oil circuit-breaker is open or closed. red and green lamps will be installed opposite each set of disconnecting-switches. These lamps will be operated by a signal-switch on the oil circuit-breaker in the same manner as the red and green indicating lamps on the control desk.

The synchronous motors of the motor-generating sets, as well as the gas-engine-driven generators for the reserve power, are to be operated from the control desk, while the railway generators and alternating-current and direct-current feeders will be controlled from panels.

II-*d. Oil-switches and circuit-breakers.* The terms "oil-switch" and "oil circuit-breaker" are used synonymously in this paper. While in a few cases the oil-switches for high-tension plants may be and are operated by hand, these cases are exceptional, and only the oil-switches or breakers intended for electrical operation will be considered. These are usually one of two distinct types, and the engineer has to weigh the relative advantages of the different designs.

One type of switch is essentially a bottom-connected motor-operated switch intended for mounting in a masonry structure with each pole in a separate fireproof compartment, and each contact in a separate pot with terminals at the bottom of the pot. The other type of breaker is essentially a top-connected solenoid-operated self-contained breaker with the two contacts forming one pole in the same tank. The different features of these two designs will be taken up in order.

Bottom-connected versus top-connected. With the bottom-connected breaker, particularly when made with a wooden pot, considerable difficulty is experienced in making an oil-tight joint where the contact passes through the bottom of the pot. The top-connected breaker does not have this difficulty to contend with. With the bottom-connected breaker, the operating mechanism is entirely separated from the leads, while with the top-connected breaker the operating-rod as well as the leads pass through the top of the tanks and are necessarily closer together than the operating-rod and the leads of the bottom-connected breaker, which are at opposite ends of the pots.

Motor operation versus solenoid operation. On one switch the operating mechanism, consisting of a motor with suitable rods, springs, clutches, etc., is located on a base above the pots and supported by the walls which form the fireproof compartments for the poles. This mechanism is ordinarily at such a height from the floor that it is necessary for the station attendant to stand on a ladder in order to oil the motor or adjust any of the mechanism.

With the solenoid-operated breaker, the solenoid toggles, etc., are located on or near the floor in such a position that the station attendants can readily inspect and adjust them while standing on the floor.

Type of oil tanks. The motor-operated bottom-connected breaker is arranged with the two pots forming one pole of the switch mounted in a common horizontal platform supported at the four corners by wooden legs. This type of switch requires a comparatively small amount of oil and has the advantage that the circuit is opened in two independent receptacles per phase. With this bottom-connected arrangement, however, the sediment of the oil tends to settle on the contacts.

The circuit between the terminals in the bottom of the two tanks forming one pole of the breaker is made through metal plunger-rods attached to a metal cross-piece external to the tanks. A motor-operated mechanism connecting through wooden rods to the metal cross-piece moves it and the plungers vertically upward to open the circuit. The exposed metal parts above the tank and the bare terminals below necessitate the enclosing of the switch in a masonry structure for the protection of the attendant. Doors are provided for each compartment of the structure to permit the ready inspection of the tanks, etc., but the removal or breaking of a door leaves these live metal parts a source of danger.

This motor-operated bottom-connected switch is the type installed in the 60,000-volt circuits of the Electrical Development Company at Niagara Falls and Toronto.

With the top-connected solenoid-operated breaker, metal tanks with insulated linings are used, and the two stationary contacts forming each pole are located under the oil near the top of the tank where sediment cannot settle on them. These contacts are, however, carefully separated by barriers so that the same result is secured as though each contact were in a separate tank.

The circuit between these stationary contacts is completed by plungers connected to a cross-arm and moving vertically downward to open the circuit. These cross-arms are connected through wooden rods to a toggle mechanism operated by a single direct-pull solenoid located on the floor in front of the breakers. All the live metal parts are completely submerged in oil, while the leads brought out through the top of the case are very heavily insulated. As the tanks, mechanism, etc., are grounded for the protection of the attendant, there is no necessity of enclosing the breaker in a masonry compartment.

The tops of the tanks are so made that the terminals, contacts, etc., can be readily got at for inspection, etc. This top-connected breaker is built in two different types, one with boiler iron tanks for very large capacities and the other with sheet metal tanks for smaller capacities.

The solenoid-operated top-connected breaker with boiler-iron tanks is the type installed on the 60,000-volt circuits of the Ontario Power Company and is guaranteed to open safely under any condition of overload or short-circuit that might arise in a plant with 200,000 kw. capacity in generators. The general appearance and over-all dimensions of this 60,000-volt breaker are shown in Fig. 3, while Fig. 4 covers a similar breaker designed for corresponding service at 120,000 volts.

The other type of top-connected breaker, intended for smaller installations and provided with sheet-metal tanks with wooden lining, is shown in Figs. 5 and 6, the former giving the over-all dimensions and the general appearance of the 60,000-volt breaker, while the latter covers the corresponding 88,000-volt breaker.

While the advocates of the different types of breakers naturally favor their own design, and while either type of breaker can be arranged to work in with a scheme of enclosed or open wiring, the bottom-connected switch is essentially designed for in-

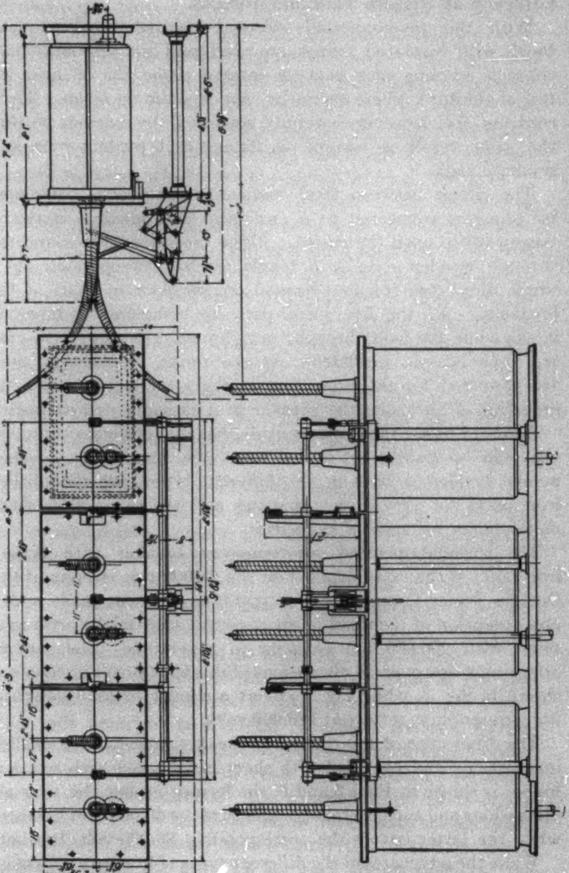

FIG. 3—60,000-volt, top-connected breaker with boiler-iron tanks

stallation where the wiring, bus-bars, etc., are placed in masonry compartments, while the top-connected breaker is intended primarily for plants where the high-tension wiring is overhead and entirely open.

The claim is made for each system that its type of breaker is less liable to get out of order than the other design. Both types are giving satisfaction under actual operating conditions, and the weak points of each breaker are being corrected as rapidly as they are discovered.

Where the control voltage is normal, the speed of operation is practically the same for the motor-operated and solenoid-operated breakers. If the operating voltage is too low, however, the motor-operated breaker closes and opens somewhat more quickly than the solenoid breaker, but with the motor-operated breaker some little time is required after the breaker closes until the motor has wound up the spring to trip the breaker out again.

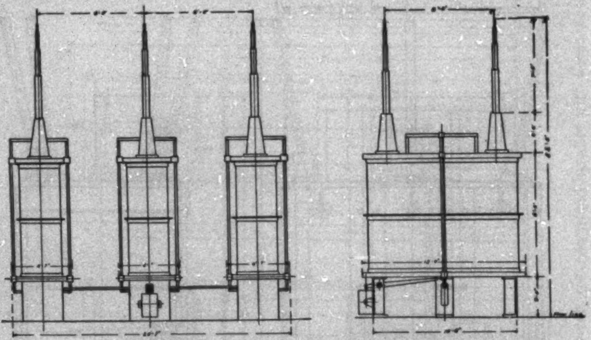

FIG. 4—120,000-volt top-connected breaker with boiler-iron tanks.

Both designs of breakers may be so counterbalanced that in case of ordinary trouble either type will tend to fall open rather than to fall closed. However, if the wooden operating-rods to which the moving contacts are attached should break, the bottom-connected breaker would tend to fall closed, while the top-connected breaker would tend to fall open. Although there is little likelihood of breaking the wooden operating-rods of either type, such an accident is possible. Under this condition the top-connected breaker would have a decided advantage.

Where it is desired to have the breakers automatic, this is done by providing either a series trip-coil, ordinarily located in the tank underneath the oil, or a series transformer. In either case the operation of the series trip or the series transformer closes the direct-current trip-circuit, instead of operating directly on the mechanism of the switch or breaker.

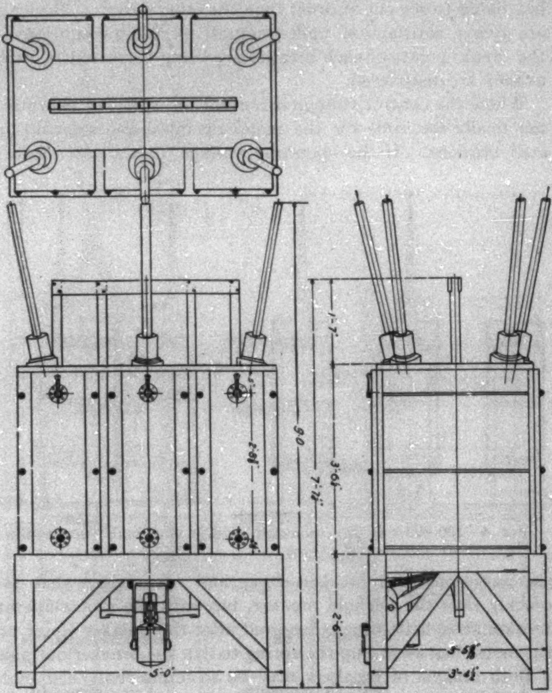

Fig. 5—60,000-volt top-connected breaker with sheet-metal tanks

The advantage of the series trip-coil is largely on account of its being cheaper, while the advantage of the series transformer arrangement lies in the increased insulation obtained and in the fact

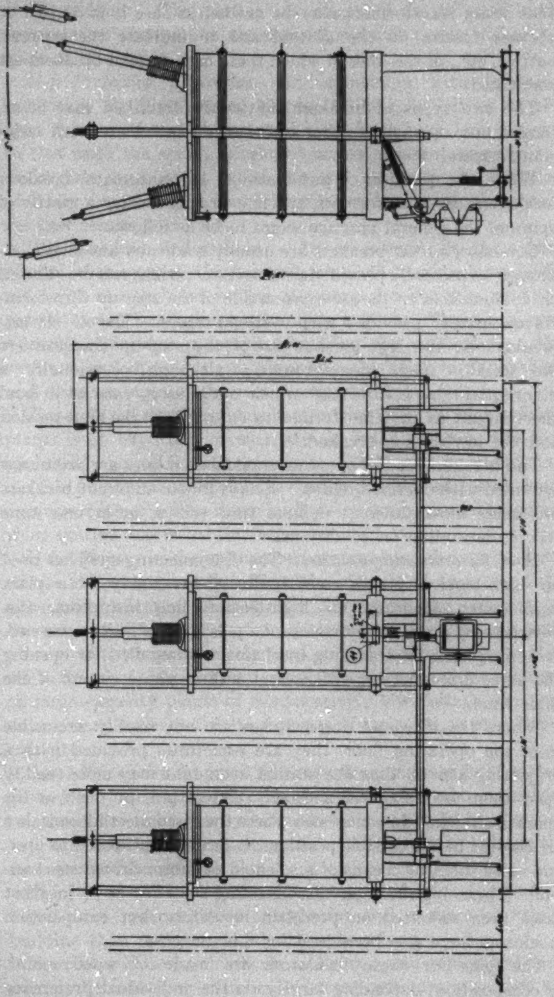

FIG. 6—88,000-volt top-connected breaker with sheet-metal tanks

that series transformers may be needed in case it is desired to operate meters on the switchboard to indicate the current, output, etc., of the lines in which these high-tension breakers are connected.

The two types of breakers previously described may be arranged for operation either with series trip-coils or with series transformers.

While the question of automatic or non-automatic breakers for generators, transformers, and line circuits is often a matter of opinion, the general practice seems to be as follows:

Generator circuit-breakers are usually made non-automatic, although occasionally provided with reverse-current relays. The oil circuit-breakers on the low-tension side of the step-up transformers are usually provided with overload relays. The oil circuit-breakers on the high-tension side of the step-up transformers are usually made non-automatic, although occasionally a differential relay is furnished which operates in case of a local short-circuit in the transformer to cut off both the high-tension and the low-tension breakers.

The breakers for the outgoing transmission lines are ordinarily provided with overload relays. Relays for the different breakers are made instantaneous, definite time relays, or inverse time relays, depending on conditions.

II-*e. Disconnecting-switches.* The disconnecting-switches used on high-tension plants consist almost invariably of a plain knife-switch mounted on high-tension line insulators, this switch being operated by means of a pole with a hook in one end. In some plants an operating mechanism is installed for opening the three disconnecting-switches of a three-phase circuit at the same time.

Where the disconnecting-switches are not readily accessible from the operating floor, they are sometimes provided with a projecting arm so that the station attendant may more readily open them by means of a direct vertical pull or push of his operating stick. In some cases where the disconnecting-switches are located in inaccessible positions, it has been proposed to open and close them by means of a solenoid or motor-driven mechanism. These high-tension disconnecting-switches have in most cases been mounted on porcelain insulators, but composition insulators have also been used for this purpose.

The pins for these insulators are made of wood, metal, or composition, depending largely on the individual preference of the designer. The relative advantages of the different kinds of insulators and pins is not a question which comes within the scope of this paper.

II-*f*. *Protective apparatus*. In connection with lightning protection for high-tension plants, choke-coils, either of the open type or of the oil-immersed type, have been largely used. In this work the strain developed across adjacent turns in the choke-coils is so great when the coil performs the function normally expected of it that oil insulation is necessary to obtain the best results.

II-*g*. *Bus-bars and wiring*. As mentioned in the earlier portion of this paper, the bottom-connected breakers are chiefly used with the enclosed system of wiring and bus-bars, and the top-connected breakers with the open system. There is a considerable difference in opinion between the advocates of the enclosed and open systems regarding the relative advantages and disadvantages of the two arrangements.

The enclosed system of bus-bars, wiring etc., for high-voltage plants is an extension of what is acknowledged to be the best standard practice for voltages up to 13,000, and is intended to provide additional safety for the station operator and additional security against a shut-down such as might be caused by something getting across the bus-bars.

II-*h*. Those who favor the open system base their arguments on the following grounds. First, the violence of an arc and the destructive effect of short-circuit depend on the amount of current available at the point of short-circuit, or, for the same amount of power, is inversely proportional to the voltage, so that while fireproof barriers and cellular construction are required on large capacity plants of comparatively low voltage, they are unnecessary for higher voltage plants of the same, or even larger capacity.

Secondly, as the fireproof barriers offer a more or less perfect ground for high-voltage circuits, the striking distance from wire to ground has to be greatly reduced over what could be obtained with open wiring in the same space. The higher the voltage the more perfect the ground.

Thirdly, the use of enclosed bus-bars and wiring ordinarily necessitates several floors or galleries and a more expensive building than is the case with the open wiring.

Fourthly, it is more difficult to inspect and repair bus-bars, wiring, disconnecting-switches, lightning-arresters, etc., that are boxed in masonry compartments and only visible and accessible by the removal of doors than if everything is in plain sight. Incipient trouble will be noticed far sooner with open wiring than with enclosed, and inspection will be more frequent and thorough if the station attendant in a few minutes' walk can see everything, than if he had to remove several hundred doors and visit two or three floors to examine the condition of the apparatus.

Typical examples of the enclosed and open systems of wiring for 60,000-volt circuits are the transformer houses of the Electrical Development Company at Niagara and Toronto, and of the Ontario Power Company at Niagara Falls.

One of the most striking differences in the two plants, due partly to the use of bottom-connected breakers and enclosed bus-bars in one case, and the top-connected breakers and open bus-bars in the other, is in the location of the disconnecting-switches which isolate the oil-switches or circuit-breakers from the bus-bars.

In the former case they are below the oil-switches and invisible from the switch-room without removing the doors of the switch-compartments, and cannot readily be opened without going down stairs. The station attendant adjusting or cleaning a breaker is on a different floor from the disconnecting-switch, which, if closed through a misunderstanding of orders by a second attendant, will make the oil-switch terminals alive, with consequent grave danger to the cleaner.

In the station of the Ontario Power Company the disconnecting switches are directly above the oil circuit-breaker, can be pulled by the attendant standing at the breaker, and cannot readily be closed without the knowledge and consent of the man working on the breaker.

III-*a*. *Present stations* 60,000 *volts*. In order to give an idea of the relative space required for 60,000-volt and 100,000-volt plants, the preliminary drawings prepared for two different stations of approximately the same capacity and same general arrangement are shown in Figs. 7, 8, 9, 10, 11, and 12.

Figs. 7, 8, and 9 show the plan, elevation, and section of the transformer and switching house to be built on the side of a hill for a plant containing eight 7500-kw. 6600-volt generators, and twelve 5000-kw. 6600- to 60,000-volt step-up transformers, with four outgoing transmission lines. In this station the transformers are delta-connected on both the low-tension and high-tension sides and knife-type disconnecting-switches have

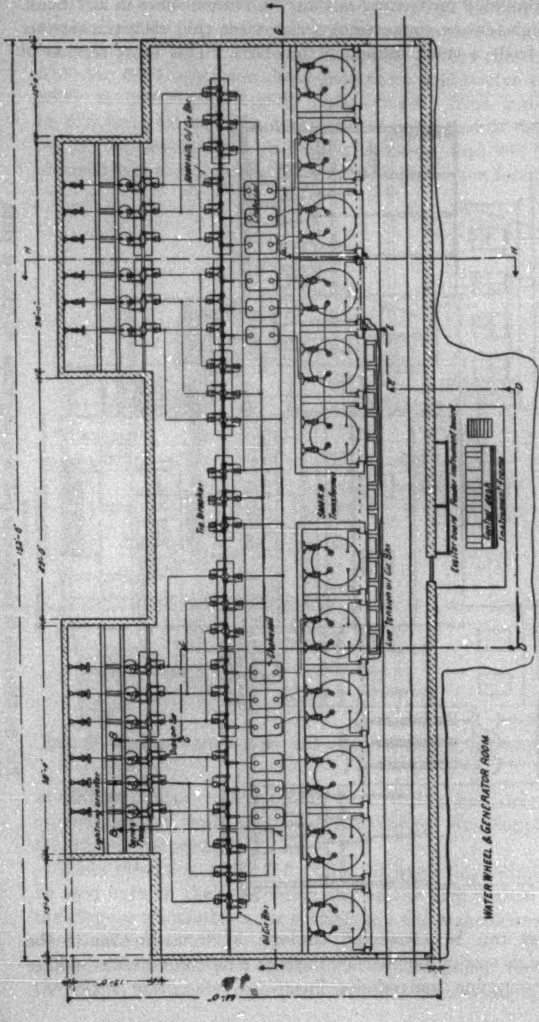
Oil Cir Bkr
Tie breaker
Transformer
Low Tension oil Cir Bkr
Exciter board
Feeder instrument board
Control desk
Instrument frame
Lightning arrester
Series Trans
Discon Sw
Choke coil
WATER WHEEL & GENERATOR ROOM
H
D
G
153'-0"
38'-0"
15'-0"
13'-0"

Fig. 7—Plan of transformer and switching house. 60,000-volt plant

been provided for cutting out any one transformer in any bank. The high-tension connections are so made that each transformer bank feeds a short section of bus-bars. This short section of bus-bars can be connected through a circuit-breaker to the main high-tension bus-bar, or through a different circuit-breaker to the outgoing transmission line.

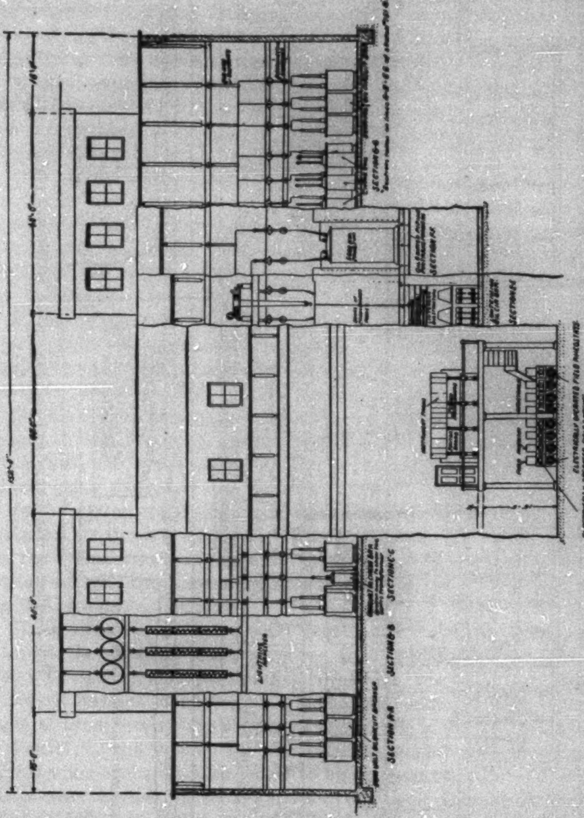

FIG. 8—Elevation of transformer and switching house, 60,000-volt plant

III-*b.* *Present stations* 100,000 *volts.* Figs. 10 and 11 show respectively the plan and section of the transformer and switching house, also on the side of a hill, proposed for the control of ten 5000-kw. 6600-volt three-phase generators, and twelve 4000-kw. 6600- to 66,000-volt step-up transformers. This station will be first installed with the transformers connected in delta both on the low-tension and on the high-tension, and will later be changed over to star connections on the high-tension for operating at 100,000 volts. All the bus-bars, wiring, etc., have been spaced suitably, and all breakers, switches, etc., supplied for this higher voltage.

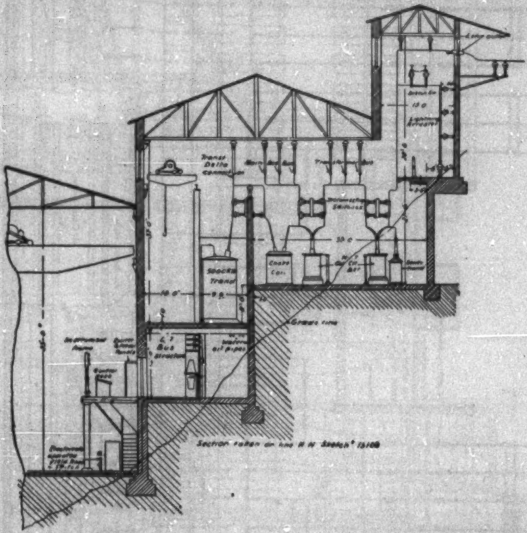
Transf. Delta connection
Disconnecting Switches
Lightning Arrester
Choke Coil
Shock Trans
L.T. Bus Structure
oil pipes
Grade line
Instrument Frame
Section taken on line H H Sketch 13168

FIG. 9—Section of transformer and switcning house, 60,000-volt plant

While operating at 66,000 volts, disconnecting-switches will be used both on the low-tension and on the high-tension side of the step-up transformers for cutting any one transformer out of the bank.

The main connections of this plant will be similar to those of the plant previously described; namely, each bank of trans-

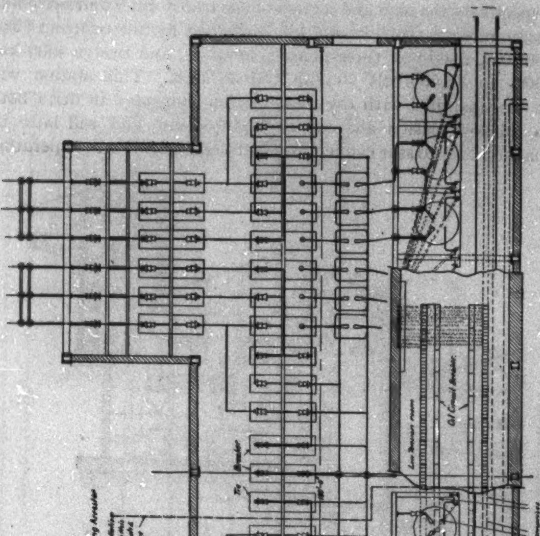
Lightning Arrester
Ammeter
Oil Circuit Breaker
Choke Coil
Transformer
Oil Circuit Breaker

FIG. 10—Plan of transformer and switching house, 100,000-volt plant

formers feeds a short section of transformer bus-bar, which transformer bus-bar can be connected through a breaker either to the main station bus-bar or through another breaker to the high-tension outgoing feeder.

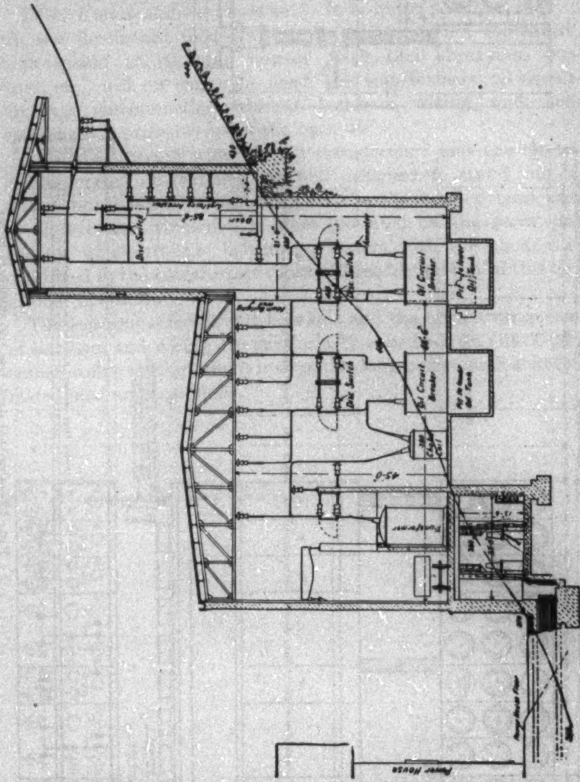

FIG. 11—Section of transformer and switching house, 100,000-volt plant

The low-tension connections are arranged on a straight double-throw system, as indicated by the miniature bus-bar on the control desk shown in Fig. 12, and it may be noted that the entire equipment of this station will not be installed at first.

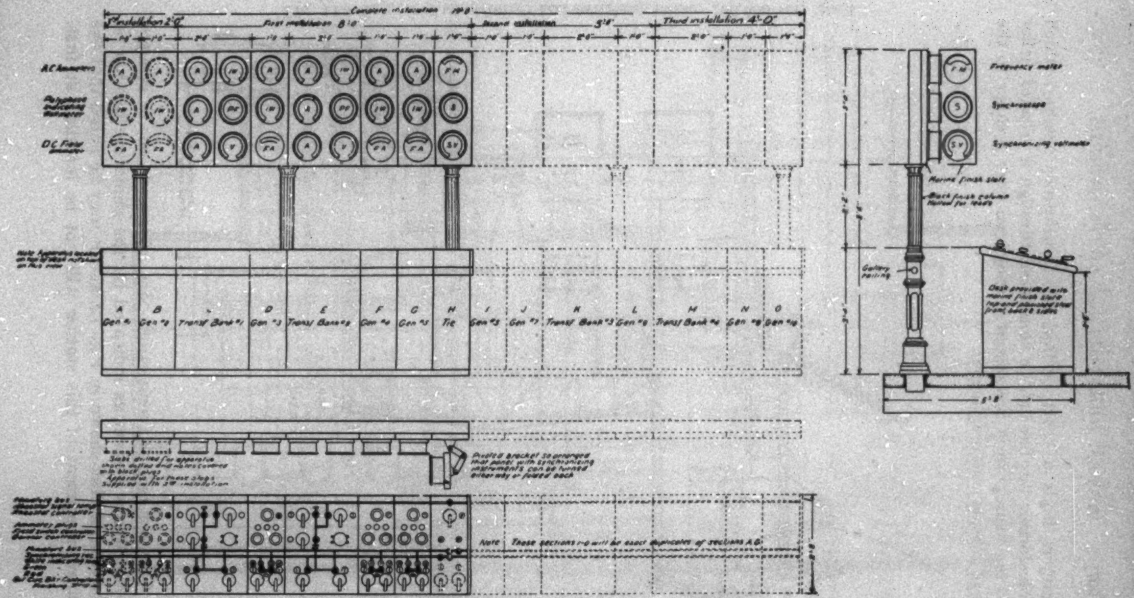
Complete installation 19'8"
3rd installation 2'0"
First installation 8'0"
Second installation 5'8"
Third installation 4'0"
A.C. Ammeters
Polyphase indicating wattmeter
D.C. Field ammeter
A
IW
FA
PF
V
FM
S
SV
A Gen. #1
B Gen. #2
Transf Bank #1
D Gen. #3
E Transf Bank #2
F Gen. #4
G Gen. #5
H Tie
I Gen. #6
J Gen. #7
K Transf Bank #3
L Gen. #8
M Transf Bank #4
N Gen. #9
O Gen. #10
Slabs drilled for apparatus shown dotted and holes covered with black plugs
Apparatus for these slabs supplied with 3rd installation
Pivoted bracket so arranged that panel with synchronizing instruments can be turned either way or folded back
Rheostat controller
Ammeter plugs
Governor controller
Note These sections I-O will be exact duplicates of sections A-G
Frequency meter
Synchroscope
Synchronizing voltmeter
Marine finish slate
Black finish column hollow for leads
Gallery railing
Desk provided with marine finish slate top and planished steel front, back & sides
5'8"

FIG. 12—Control desk for 100,000-volt plant

IV-*a. Future stations; indoor.* As may be noted from Figs. 6 to 11 the amount of space necessary for the circuit-breakers, switches, bus-bars etc., for a high-voltage transmission plant is comparatively great and it requires a large building to contain them.

IV-*b. Future stations; outdoor.* It is quite possible that in the not far-distant future where the climate is not too severe, high-tension transformer houses with their breakers, bus-bars, etc., will no longer be used; the transformers, oil circuit-breakers, disconnecting-switches, bus-bars, wiring, and connections will probably be in the open air.

The oil-immersed water-cooled transformers and the electrically-operated oil-switches are well designed to stand out-of-door conditions. Disconnecting-switches have often been used in high-tension transmission lines mounted on the poles, and the use of electrolytic lightning-arresters with the choke-coils combined in the transformer cases will readily permit of this out-of-door operation.

The top-connected circuit-breakers and the open arrangement of bus-bars and wiring are particularly suited for an out-of-door transforming station, and it may not be long before such a station is designed and installed.

DISCUSSION ON HIGH-TENSION TRANSMISSION PAPERS AT NIAGARA FALLS, N. Y., JUNE 26, 1907

P. M. Lincoln: An inspection of some of the illustrations shows that there is a very apparent angle in the cables at the point where they are attached to the tower structures at the bottom of the gorge. This angle would indicate that the strain at that point is downward. I would like to know why this method of construction was used. It surely cannot be on account of relieving the supports at the top of the bank of strains due to a long span, because the strains in the cables must necessarily be increased by the amount of the downward strain at the point where they are attached to these structures.

F. B. H. Paine: The cables drop from the cantilever loosely to the river-edge tower on which they are dead-ended. The cantilevers support the weight, and the water-edge towers simply hold them out of the vertical sufficiently to prevent their hanging too close to the steep hillside.

P. M. Lincoln: It seems to me that exactly the opposite effect would be obtained by this construction, since the curve which would naturally fall would be made more abrupt by pulling down at this point.

F. B. H. Paine: The span across the river is quite independent of the slope-spans, and is dead-ended on each water-edge tower. The crossing is not a catenary into which the water-edge towers are inserted and steady the cables. It is three independent dead-ended spans; two almost vertical and one almost horizontal.

P. M. Lincoln: I do not see why it is necessary to attach to the towers at that point.

F. B. H. Paine: Mr. Mershon divided the crossing into the three spans to avoid the effects of tremendous winds in the Niagara Gorge—blowing both ways at once—and which unusual condition he feared would result in swinging the cables together. He wanted as short a span as possible and as close to the bottom as possible, to avoid the effects of the cross-winds on one span. I believe our experience shows that the effect of these winds was exaggerated by the "oldest inhabitant."

D. B. Rushmore: Some of Mr. Mershon's power consumers get their power from a single line, and I think it is open to discussion whether such a practice is justified. In the line construction shown, some pertinent questions arise; for instance, from the experience given in the paper by Mr. Rowe, it has been found necessary to put the top conductor below the others, and to run the ground wire in its place. I think that a similar change would be desirable here.

The questions at once arise, why are the wires on separate towers? Why is a single tower not used to carry both sets of wires? Under what conditions can one high-tension line near another be repaired while the other is in operation?

Mr. Buck shows a line construction for very high voltage and he puts both lines on the same tower. Can he repair one line if the other is in operation?

The wooden A-poles which Mr. Mershon shows have got to be replaced every eight years, we will say, but not all poles will last eight years. Every time a pole is replaced, the transmission of power is interrupted, and while at first the interruptions from this cause are not many, they finally become so frequent that customers grow impatient and new customers cannot be got. Under these conditions it seems to me that a single line transmission with a wooden pole construction is not economically justified.

H. W. Buck: Regarding the possibility of working on one line with the other line alive: in Fig. 2, with the tower grounded and with the circuit out of service grounded, I see no reason why a man should not safely work on that dead circuit. He would have the whole tower structure between him and the live circuit, and the circuits are quite a distance apart, about 20 feet.

J. B. Taylor: Mr. Nicholson's method of locating breaks, or more properly grounds, on high-tension lines is extremely valuable, the broken insulator being the trouble which is most often experienced. I think that the transmission system on which he has made his tests was fortunate in having a man who could take up work of this sort, possess the proper ingenuity to make the proper application for the particular trouble, and be on the ground when the trouble came; but I doubt if the average transmission plant will install the necessary switches and resistances and have the experts to locate troubles in this manner.

A plant that was started up about five years ago had a fourth wire installed on a three-phase system. The idea was that when one of the three wires got into trouble, a simple system of knife-switches could cut in the fourth wire, and everything would go along as usual. The line has had occasional trouble, but for one reason or another—either because the operating force did not feel sufficiently sure of the conditions to cut in the spare wire, or because they felt that the trouble was of such a nature that it was unsafe to attempt to resume service before knowing what the trouble was—the fourth line has not been used.

I have not checked the mathematical equations in the paper, but offhand it is not obvious why the reactances of the long and short sides of the loop should come out in the same ratio as the resistances. The inductive effect of the return current in the earth does not appear in the analysis, and under some conditions this appears to be an essential factor. However, the accuracy of the test locations shows the method to be right for the average transmission line when the two sides of the circuit are separated by a few feet.

Without doubt Mr. Nicholson has considered other schemes for locating these troubles. I wonder if he has tried to locate a broken insulator by merely passing the current over the faulty wire to ground and measuring the induced voltage in a neighboring wire—one of the transmission wires, neighboring telephone lines, or anything that happened to be handy. Assuming the wires at uniform separation, the induced voltage should be proportional to the length.

William McClellan: It appears as if every essential point had been considered in the design of Mr. Hewlett's insulator. In the long run it should be cheaper, though the first cost would remain the same as for present types. Those of us who have had experience with large 60,000-volt insulators made of cemented shells know what it means to discard an insulator because of a simple broken shell. Another point is the benefit of the full dielectric strength of the material used. We all know that the breakdown potential of a cemented insulator is considerably less than the sum of the breakdown potentials of the separate shells.

Regarding Mr. Hayes' paper, I think emphasis should be laid on the desirability of the open type of wiring for potentials over, say, 25,000 volts. For higher potentials there is a strong tendency among engineers toward outdoor stations, though it must be acknowledged that the last word on this subject will not be said for some time to come. I think that we should cease putting up ordinary knife-switches to be opened with a pole in the hands of a man on a shaky platform 25 feet from the ground. Very simple switches to be opened from the ground have been designed by certain operators in the West and marked attention should be given to this simple but, at times, very important part of the high-tension apparatus.

W. N. Smith: Has the matter of icicles forming between the successive petticoats of insulators of the type proposed by Mr. Hewlett been given due consideration? It would seem as though a chain of insulators, one above the other, might perhaps enable icicles to be formed that would connect from one disk to another. Unless there has been experience to the contrary, I should hesitate to condemn the ordinary petticoat type on account of icicle formation between petticoats, which I think would be fully as difficult to consummate with the petticoat type as with the new insulator proposed by Mr. Hewlett.

L. C. Nicholson: In regard to Mr. Taylor's suggestion as to measuring voltage generated in a parallel wire, I will say that some such methods have been undertaken, but the results obtained were not encouraging, particularly on account of parallel circuits which were in operation at the time, interfering with any measurements of induced voltage in the parallel wire. In case of only one line, I presume some such test could be made, but having more than one line one interferes with the test on the other by electrostatic and electromagnetic induction. In any case, I think it would be necessary to have two instruments; an ammeter to measure the current flowing, and a voltmeter to measure the induction.

S. Q. Hayes: The 200,000 kw. given as the capacity of the oil circuit-breaker is correct; that is, the manufacturers guarantee that that switch will be able to open any overload or short-circuit that will occur on the station having that capacity on the bus-bars. Up to the present time there is no station with that capacity on the bus-bars.

In connection with the troubles in pulling disconnected-switches, it has been proposed in several cases where the disconnecting switches are in rather inaccessible positions to operate, them by means of a soleloid or motor-driven mechanism.

J. H. Finney (by letter): It seems to me that Mr. Mershon's method of tying-in is not so simple as might be employed, although the tie is very ingenious; the chief objection to it is the large amount of tie-wire required, and the fact that the cable is not firmly fastened to the insulator, but simply lies in the top groove.

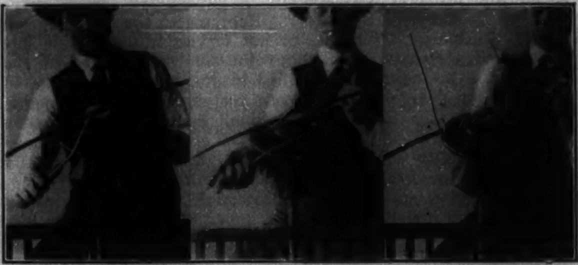

FIG. 1. FIG. 2. FIG 3.

I would like to call attention to a tie which not only embodies simplicity and a small amount of tie-wire, but has the advantage of holding the conductor firmly on every side, as will be seen by the accompanying illustrations. The tie is made by straddling the line wire and top of the insulators as shown in Fig. 1. Both ends are then carried around the neck of the insulator in the same direction as shown in Fig. 2. Having made a half circle of the insulator, the ends are made off by taking a number of turns around the line conductor shown in Fig. 3. This makes a symmetrical tie, the conductor being held without danger of kinks, and is not subjected to any strains which would tend to cause abrasion and breakage of either tie-wire or conductor. The strain is uniformly distributed around the head of the insulator, the conductor being held firmly in the groove. This tie is decidedly cheaper than clamps, is more easily installed, and, in my opinion is not only more desirable than clamps, but is one of the best designed ties, from all standpoints, of which I have knowledge.

F. G. Baum (by letter): When trouble occurs on a line similar to that considered by Mr. Nicholson, the station operator will try to find the section of line on which the trouble is located. The trouble may be a broken insulator, or it may be more serious, and repeatedly to throw power on a disabled line to test it may at some time cause very serious consequences. Furthermore, having located the section of the line in trouble, the operator will at once start patrolmen from each end of the section. After the point at fault is located it will require one man, and very often two men, to repair the break. Until the men arrive at the break it is not certain what must be done and what materials will be required. Hence, while the test method may be of some advantage in some cases, generally one would have to use the sure way in addition to it. Power should not be thrown on a disabled line more than necessary, as life and property may thereby be endangered.

Ralph D. Mershon (by letter): Replying to the points raised by Mr. Rushmore. Whether or not service from a single line is justified, depends upon the value and importance of the customer. One would be justified in going to the expense of two lines for a large and important customer, but such expense would render the business of a small customer unprofitable. Mr. Rushmore raises the question of the grounded wire. I have never been fully convinced that the grounded wire actually affords an appreciable amount of protection against lightning, or, at any rate, an amount of protection which would justify the expense of installing it. I had hoped that Mr. Rowe would, in his paper, bring more convincing proof of the value of the grounded wire than has been submitted in the past by those defending it, but I must say I cannot see that he has done this. The question of two-circuit towers vs. single-circuit towers is one on which many arguments can be advanced on both sides. In the end, the choice must be largely decided by the conditions to be met. In our case it seemed best, for a variety of reasons, to make use of the single-circuit towers. What Mr. Rushmore says in regard to wooden pole-line construction is true in many cases; it is not true in this case however. Where the A-frames were installed, the amount of space available was not sufficient to allow of tower construction, and steel-pole construction would not only have been more expensive than wooden poles, from every standpoint, but the necessary deliveries of steel poles could not have been obtained.

As regards Mr. Finney's tie, I would say that the tie we used was adopted for the reasons set forth in the paper, and only after an exhaustive series of tests on all the ties we knew of or could devise. If Mr. Finney will make actual pulling tests on his tie with aluminum cable and aluminum tie wire, he will find, I think, that it will not fulfil the conditions which, as explained in the paper, it was desired to meet, and which the tie adopted does meet.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

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DEFLOCCULATED GRAPHITE

BY EDWARD G. ACHESON

The subject-matter of this address is not in any sense electrical in character, but the effect described was discovered as the result of electrical work and the products obtainable by it may, with advantage, be used in electrical work and machinery. Such is my excuse for offering these remarks before this Institute.

In the year 1901, I was engaged in a series of experiments having as their object the production of crucibles from artificial graphite. In this work I was led into a study of clays. What I learned may be briefly stated as follows: 1. The American manufacturers of graphite crucibles imported from Germany the clay used by them as a binder of the graphite entering into the crucibles. 2. The Germany clays are much more plastic and have a greater tensile strength than American clays of similar chemical composition. 3. Residual clays—those found at or near the point at which the parent feldspathic rock was decomposed—are not in any sense as plastic or strong as the same clays are when found as sedimentary clays at a distance from their place of origin. 4. Chemical analysis failed to account for these decided differences.

I reasoned that the greater plasticity and tensile strength were developed during the period of transportation from the place of their formation to their final bed, and I thought it might be due to the presence of extracts from vegetation being in the waters which carried them. I made several experiments on clay with vegetable extracts, tannin being one of them, and I found that a moderately plastic, weak clay, when treated with a dilute solution of gallotannic acid or extract of straw, was increased in plasticity—made stronger in some cases as much as three hundred per cent.—required but 60 per cent. as much water to produce a given degree of fluidity, was caused to remain suspended in water, and made so fine in particles that it would pass through a fine filter-paper. Being acquainted with the record of how the Egyptians had the children of Israel use straw in the making of bricks, and believing it was used not for any benefits derivable from the weak fibres but for the extract, I called clay so treated Egyptianized clay.

Having in 1906 discovered a process of producing a fine pure unctuous graphite, I undertook to work out the details of its application as a lubricant. In the dry form, or mixed with grease or oil, it was easy to handle, but I wished it to enter the entire field of lubrication as occupied by oil. In my first efforts to suspend it in oil I met the same troubles encountered by my predecessors in this line of work; it would quickly settle out of the oil. My unctuous graphite was just plain simple graphite, and obeyed the same laws covering the natural product. So things stood until the latter part of 1906 when the thought occurred to me that tannin might have the same effect on graphite that it had on clay. I tried it with satisfactory results. I will now show you the effect and how it is produced.

I will take for the experiment two equal quantities of my unctuous graphite, as produced in the electrical furnace. When in this form, I call it disintegrated unctuous graphite. To one sample I will add plain water, and, after rubbing up in a mortar, I pour it into a test tube. To the other sample I will add water, a little gallotannic acid, and a few drops of ammonia. This last is not always necessary, but I find it improves the results with some waters. I will now rub the mixture in the mortar as in the first case, and then pour into a test tube. I will now shake up both tubes simultaneously and place them in a rack to settle.

Two minutes have now elapsed since the shaking and we find the graphite in the plain water has very completely separated from the water, not being miscible therewith, while the mixture of graphite, water, tannin, and ammonia remains as black as when shaken up. The graphite is miscible with the water in this mixture; it is suspended and would continue so indefinitely, at least I have found it to remain so for months, and I do not see why it should settle or separate the next day, week, month, or year.

While this experiment, as you have seen it performed, shows the effect, the result is much improved by time. I have here a bottle in which there are graphite, water, tannin, and ammonia which have been mixed for some weeks. The graphite is in what I call a deflocculated condition, a condition of fineness beyond that attainable by mechanical means, a condition approaching, if indeed not actually attaining, the molecular state. It is so fine as to pass with ease through the finest filter-paper. Here I have a glass funnel containing one of the finest filter-papers manufactured, and on this paper I will pour a little of the water and deflocculated graphite. See it run through the paper and collect in the tube, as black as ever and apparently unchanged. In fact it remains so black and has passed through so rapidly that a doubt exists in your minds as to its really being a mixture of water and solid matter—water and graphite. I can quickly convince you that such is the case.

Into the test tube containing the black liquid which has passed through the filter, I will now introduce a few drops of hydrochloric acid, and then slightly warm it over this spirit-lamp flame. These acts have caused the suspended graphite to floccluate and when I now pour the liquid onto a second filter paper, you see the water run through clear, the graphite remaining on the paper. Removing a little of the graphite and smearing it on a piece of paper, drying the paper and rubbing the black spot, it is at once recognized as graphite. This effect is obtainable with amorphous bodies generally; I have obtained it with alumina, lampblack, clay, graphite, and siloxicon.

I have successfully used deflocculated graphite in water instead of oil in sight drop-feed oilers and with chain-feed oilers. I have a shaft in my laboratory measuring $2\frac{5}{16}$ in. in diameter, revolving at 3000 revolutions per minute in a bearing 10 in. long that had no oil on it for a month, deflocculated graphite being the only lubricant used, the feed being by chain, and it ran perfectly. On the same shaft is a similar bearing lubricated with oil; this runs much the warmer of the two.

A few days after this test was started a pessimistic friend remarked that just plain simple water would give the same results, that the presence of graphite was unnecessary. We are influenced by the opinions of others even when we know or think they are wrong, so I emptied the oil out of the second bearing on the shaft and substituted plain water. The results during the first twelve hours seemed to support the contention of the friend. The next day after the machine had stood motionless over night things did not look so rosy for the water; it was a lame second on account of rust and was hurriedly removed. I think I shall not recommend clear water as a permanent lubricant.

Deflocculated graphite in water possesses the remarkable power of preventing rust or corrosion of iron or steel. This graphite, even after flocculation, is so fine in its particles that when dried *en masse* it forms a hard article. I have here a cake of dried deflocculated graphite. You can see it has the curvature of the watch glass in which it was dried. No pressure was used on it, but still you see it is comparatively hard, like a sun-dried clod of clay. It is self-bonding.

While, as I have stated, deflocculated graphite in water is an efficient lubricant, it has the drawback or disadvantage of losing its water by evaporation. I also appreciated that much time would be consumed in converting the world to water lubrication from the present one of oil. Therefore I set before me the problem of replacing the water medium with oil. A very great deal of difficulty and many discouraging conditions were met with, but I am pleased to say success was arrived at, and I have here a bottle containing kerosene oil holding about one-half per cent. of deflocculated graphite, that percentage being sufficient for most work. Here is another bottle containing spindle oil with a like percentage of graphite. The graphite has been in these oils for some weeks and shows no tendency to separate or to settle.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907

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SINGLE-PHASE VERSUS THREE-PHASE GENERATION FOR SINGLE-PHASE RAILWAYS

BY A. H. ARMSTRONG

The introduction of the alternating-current single-phase railway motor calling for a single-phase secondary distribution system makes it pertinent to inquire into the question of power generation and primary distribution for such systems. While the simplicity of single-phase generation and distribution is unquestioned, it is not always possible or desirable in these days of general power distribution to install a generating station and primary distribution system capable of taking care of alternating-current railway load alone, to the exclusion of synchronous converters and other receiving machinery requiring three-phase input.

As the use of either the single-phase or the multiphase generator seems to be open to certain objections, various methods of distribution are presented herewith, with some of the advantages and disadvantages pertaining to each.

SINGLE-PHASE GENERATION

1. Single-phase generation and transmission makes it impossible to use synchronous converters, self-starting synchronous motors, or induction motors starting under load. Poorly adapted for general power distribution, it is chiefly limited in application to alternating-current railway operation; its use is, therefore, open to grave objections of a commercial nature where there exists any possibility of selling power or in any way utilizing it for general converter and motor work.

2. The single-phase generator has an unbalanced armature reaction which is the cause of considerable flux variation in the

field pole-tips, and in fact throughout the field structure. In order to minimize eddy currents, such generators must, therefore, be constructed with thinner laminations and oftentimes poorer mechanical construction, resulting in increased cost of the generator. The large single-phase armature reaction results in a much poorer regulation than that obtained with a three-phase generator; it calls for increased amount of field copper; it requires more liberal design; it also requires larger exciting units—these make the cost of the single-phase generating unit throughout considerably more than that of a three-phase unit of the same output and heating.

The difficulties of single-phase generator construction appear to increase with decrease in frequency. The adoption of any lower frequency than 25 cycles may therefore result in serious difficulties in construction for a complete line of machines of the single-phase type, especially of the two- or four-pole turbine-driven type, where the field flux is very large per pole.

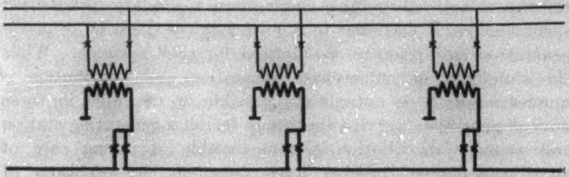

FIG. 1—Single-phase primary and secondary distribution

3. To offset the difficulty of single-phase generator construction, its greater cost and poorer efficiency, there are the advantages of simplicity in the entire generating, primary, and secondary distribution systems for single-phase roads. These advantages are so great that they justify considerable expense; looked at from the railway point of view only, the single-phase system throughout may be considered as offering the most advantages.

THREE-PHASE GENERATION

Three-phase generation and distribution is in almost universal use. Many single-phase railways receive power from such systems. The commercial advantages resulting from the use of such generators may in certain cases justify the complication of single-phase secondary distribution obtained from a three-phase source. As these commercial advantages are in many cases controlling, various combinations of three-phase–single-phase connections are presented herewith.

1. *Three-phase generation and primary distribution to motor-generator sets feeding into the single-phase secondary distribution.* This system has all the advantages of obtaining power from a three-phase distribution which may also feed synchronous converters and a general power load; it is independent of the frequency of the generating system, being equally adapted for 60 or 25 cycles. It is the only system which will give perfect balance on a three-phase distribution system. Its disadvantage lies in the cost of the motor-generator sub-station.

2. *Three-phase generators operating alternating-current railway load on one leg, thus calling for both primary and secondary single-phase distribution.* Commercial considerations of a possible future synchronous converter or power load may justify the installation of three-phase generators designed for single-phase output for railway load and three-phase output for general power distribution. This system is open to the objection of serious unbalancing due to railway load on one phase only, and this unbalancing may be so great as to cause undue heating in synchronous converters, synchronous motors, and induction motors fed from the unequal potentials of all three legs of the three-phase generator. Tests have been made which indicate that receiving apparatus may have its capacity reduced from 30 to 50 per cent. with normal heating with the unbalancing caused by a single-phase railway load fed from a three-phase generator in commercial operation.

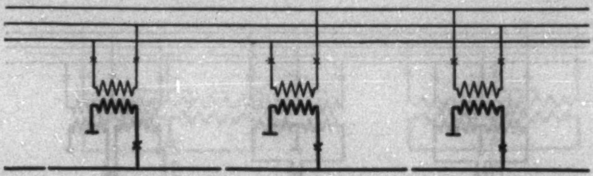

FIG. 2—Three-phase primary and single-phase secondary distribution

A three-phase generator run as a single-phase generator is open to all the objections of excessive armature reaction, poor regulation, and pulsating flux in field structure noted above for single-phase generators. Such generators must be rated single-phase at two-thirds or less of their output when operating on a balanced three-phase load.

3. *Three-phase generation and primary distribution to sub-station, feeding successive trolley sections with separate phases.* Where the length of the road is sufficient to permit sectionalizing the trolley into three sections, or multiples of three, having an equal load on each section, this method provides for balancing the three-phase load, thus securing full output of the generator, non-interference with power load, etc. Each sub-station must contain two sets of transformers connected to separate phases, so that adjacent sub-stations may feed like phases into a common trolley section extending between them. The installation of a single transformer in each sub-station would necessitate the sectionalizing of the trolley midway between sub-stations, hence losing half the effective value of the copper as obtained with the trolley sectioned at the sub-stations and two adjacent sub-stations feeding a common trolley section.

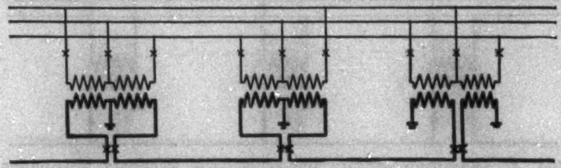

FIG. 3—Three-phase primary and single-phase secondary distribution

This method of obtaining a balanced three-phase load is open to the objection of complication and possible ineffectiveness, with serious disarrangements of schedule such as take place in railway operation during different periods of the day and season.

4. *Two-phase generation, generating station located in center of system and feeding one phase each way.* So long as the load is balanced upon the two primary distribution systems, this method of connection is capable of good results; but operation under the necessities of commercial service shows it to be very difficult to balance the load upon the two phases, thus resulting in considerable unbalancing and extreme voltage variation on the less loaded leg. This same criticism holds true of method 3.

5. *Three-phase generation and primary distribution to transformer sub-stations connected three-phase–two-phase, and*

feeding secondary distribution in such manner that adjacent sub-stations feed like phases into a common trolley section. This method of connecting is capable of giving good results in operation, although occasional serious unbalancing may occur in the primary distribution with a disarrangement of schedule or improperly proportioned trolley sections. Each sub-station must contain two transformers for regular service, and possibly one spare; these, together with the necessary switchboard arrangement, increases the complexity and cost of such sub-stations compared with the simpler arrangement possible with straight single-phase distribution.

There are other methods of connection, such as independent transmission lines to several outlying sub-stations, thus giving the generating station operator the opportunity to balance the load on the several phases of the generators; but the methods outlined are those commonly proposed for single-phase secondary distribution used in connection with three-phase generation and primary distribution.

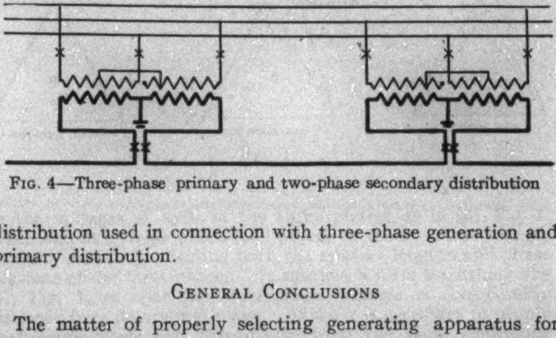

FIG. 4—Three-phase primary and two-phase secondary distribution

GENERAL CONCLUSIONS

The matter of properly selecting generating apparatus for single-phase roads seems to be closely connected with questions of a commercial nature relating to a possible future load requiring a three-phase input. From a purely engineering standpoint, and considered from the point of view of the railway load only, the single-phase system of generation and distribution is to be recommended. The possible installation of generators having a lower frequency than 25 cycles would help this decision, owing to the unfitness of such a low frequency for general power distribution work.

Of the several methods of single-phase combinations proposed, the motor-generator set best protects the three-phase distribution system where power is purchased from foreign distributing systems, and such a method presents many advantages which may outweigh its increased first cost. Where the railway company finds it expedient to generate and distribute its own power from three-phase generators, the use of a single leg for the railway load (3) or the installation of three-phase–two-phase transformer sub-stations (5). Both seem to offer advantages justifying their recommendation, the choice between the two may perhaps be left to the needs of local requirements.

Discussion on "Single-phase *versus* Three-phase Generation for Single-phase Railways", at Niagara Falls, N. Y., June 27, 1907

P. M. Lincoln: I agree with the author of this paper, that it is highly desirable to keep power service and street railway service separate if it is at all possible. However, at times commercial considerations may make it essential to supply both polyphase power service and single-phase railway service from the same generating station. When that is necessary, the author of this paper has pointed out several methods by which it may be accomplished. There is one modification, however, which he has not mentioned, but which I believe has considerable advantage over any of the methods mentioned by the author.

The ordinary three-phase system may be represented by an equilateral triangle, in which the three sides of the triangle will be the voltages of each of the three phases, as in (*a*), Fig. 1. When we put a single-phase load on one of the legs, this triangle becomes distorted, affecting both the relative lengths and phase relations of the three phases. It assumes a form something like (*b*), Fig. 1, so that the three-phase triangle is considerably distorted from its original shape. When it is necessary to supply both single-phase and three-phase from the same generating system, we can give the three-phase voltage an initial distortion so that a true three-phase relation shall lie somewhere between the initial distortion selected and final distortion which may be expected due to the single-phase load. By this means the maximum unbalancing that can take place in the three-phase circuit is approximately one-half what it would be if we started with a balanced three-phase. Fig. 1, (*c*) shows roughly in diagram the condition that might be expected. At best the effect on the three-phase circuit is anything but good.

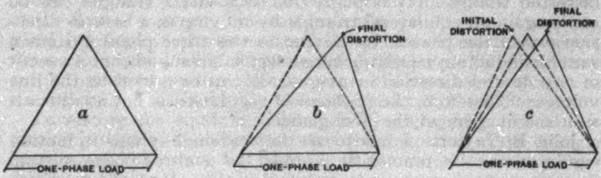

Fig. 1

Therefore, I do not feel like recommending any method or any system where a single-phase railway and a general power distribution are drawn from the same generating system; but, as I have already said, commercial considerations sometimes make it necessary to consider such a system.

Henry G. Stott: One other method, not mentioned in the author's paper, might be brought up for discussion; that is, the method of using the grounded neutral on the three-phase system. Where power is required for general purposes, as well as for single-phase railroad work, this method might be applicable, as, by the use of partly loaded induction motors in different parts of the line, the balance of the phases and also of the voltages would be restored. This makes an extremely simple combination where general three-phase power, as well as single-phase operation, is required.

V. Karapetoff: It seems to me that where difficulties should arise, on account of unbalancing, in cases where single-phase and three-phase lines are fed from the same generators, we would have to regulate the three-phase system by means of induction regulators. It is not necessary to regulate the three legs; only one phase needs to be regulated. The triangle of voltages is originally an equilateral triangle; then it becomes a distorted triangle. It is plain that this latter triangle can be made again an equilateral triangle by moving in a certain direction *one* of the phases, by having in the three-phase system a suitable induction regulator in one leg, so arranged that a vector of any desired direction or magnitude can be added to the line voltage. Therefore, the problem of regulation is not as difficult as it might seem at the first glance.

John B. Taylor: I fail to see how a single-phase induction regulator can be practically applied to a three-phase system in such a way as to compensate for the unbalancing effects of a single-phase load. More important than the drop in voltage due to line resistance, etc., is the distortion due to the reaction in the generator under single-phase load conditions.

All things considered, there will be many cases where the expense of the motor-generator set will be justified. This enables the transmission system to work on balanced three-phase load, at unity power-factor, and also removes the grounds from the transmission system. Where the single-phase load is taken as a part of a large system, unless transformers or motor-generators are introduced, a ground on the single-phase system involves, of course, a ground on the entire system and this in many cases would be decidedly objectionable.

William McClellan: The paper has reference to large systems giving opportunity for sectionalized distribution. So far, single-phase electrification has been over short distances with not more than two sections to be fed. Such a system presents little difficulty where a company is generating its own power. While from a technical standpoint the unbalancing may be inconvenient, it does not affect the coal-pile seriously. When, however, power is bought from a power company and taken from three-phase transmission lines, the effect is more serious. Under modern contracts for power, unbalancing over a certain maximum amount, must be paid for. Under such conditions it is possible to connect the transformers in V which, however, would never give a balanced three-phase load. A better method is to connect the transformers in T and use the 90° phases on the two sections of the trolley. When these two sections are equally loaded, the three-phase load will be balanced and the average balancing of the load will be considerably better. Such a system requires, however, that the three legs at the high-tension side of the transformers be opened nearly simultaneously.

Chas. P. Steinmetz: The problem of taking care of single-phase loads on three-phase systems is rather complicated. I do not believe any induction regulator can take care of it to the extent of balancing the load. The cause of the unbalancing on single-phase load is to be found in the flow of power which with single-phase load is not constant, as it is with the balanced three-phase system, but pulsating. This pulsating flow of power gives a pulsating armature reaction; superimposed upon the fundamental sine wave of the generator it produces the effect of a double frequency pulsation or magnetism due to the pulsation of the flow of power. This results in the production of a strong third harmonic. In some conditions, in extreme cases where the single-phase load is short-circuited, this triple harmonic may reach disastrous values, 250 per cent. of the normal voltage, or even more. This is merely the extreme case of unbalancing.

To restore the equilateral triangle by giving it an initial distortion is open to the objection that the distortion of the triangle is not always the same but depends on the nature and the power-factor of the load. If the power-factor of the load is approximately constant, within a moderate range, as with single-phase railroading, this can be done. But, after all, with any generator of reasonably good regulation, the matter usually is not serious because an induction motor can take care of a very great distortion of the equilateral triangle and still work with no appreciable change in efficiency, no appreciable change of heating. In most cases then we can let the triangle become as distorted as it chooses, and the induction motors and other apparatus will show no difference, except perhaps synchronous converters. Synchronous converters in such systems would necessarily be installed, as they usually are in railway work, with heavy reactances, reactances of ten per cent. or more in the leads. This reactance, by phase displacement of lead or lag, can take care, not only of line drop and control of voltage, but also of distortion of the triangle, and thus supply at the converter the equilateral triangle with a greatly distorted generator triangle, by merely a small change in the angle of lag of the three different phases, one of the three currents lagging perhaps while the other is leading to a small extent. So the converter can also take care of itself.

The main difficulty is where lighting is done from several phases. But even there, if we look at the distortion of the triangle with single-phase load, we find that naturally the loaded phase drops with the ordinary single-phase load. Of the other two phases, one drops more than the loaded phase and the other remains practically constant; that is, of the two unloaded phases the distortion is such as to keep one of the phases almost constant and in that phase through a potential regulator which has relatively little work to do, constant potential may be supplied. That is probably the simplest way of taking care of unbalanced loads. My old scheme, the monocyclic system, was to build the generator three-phase; use one phase for lighting and maintain it at constant voltage, and carry the three-phase load by the auxiliary phases. After all, that was another form of Mr. Lincoln's proposition to start with a distorted three-phase system and use the distortion to distribute the load between the different circuits in the desired manner.

A. H. Armstrong: I am inclined to look at this matter a little more broadly than some of the previous speakers. For instance, the method proposed by Mr. Lincoln can be used successfully in cases where the railway company generates its own power, although in such cases the company would have the privilege of generating and distributing single-phase power, and the simplicity of single-phase distribution would recommend it above all others. We are confronted, however, with the problem of power purchased from foreign concerns, and the tendency of the times seems to be toward establishing large centers of power distribution. The generation and distribution of power is carried on as a separate business by itself. It may be associated with lighting, railway, and power industries, but in any case it is generated and distributed three phase. It is a very difficult problem to connect single-phase railway systems to a three-phase power distribution system without interfering in some degree with other uses of a common power supply. In fact, managers of power distribution systems are very loathe to make contracts which involve the use of single-phase power for railway purposes. In such cases the introduction of a motor-generator set seems almost necessary, aside from the question of frequency supply, if the distribution circuit of the power producers is to be properly safeguarded.

Unfortunately, in a large number of single-phase projects suggested, the margin of profit between installing alternating-current apparatus and direct-current apparatus is rather small. Owing to the inferiority of the alternating-current railway motor, there is no advantage in adopting alternating-current car equipments unless there is a considerable reduction either in first cost or operating expense, or both. The added expense of motor-generator sets oftentimes acts as a serious handicap when considering the installation of alternating current railway equipments fed from a foreign three-phase source of supply. In such cases it will be necessary to use some of the methods proposed for balancing the load on the three phases rather than consider the expense of a motor-generator set.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

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THE CHOICE OF FREQUENCY FOR SINGLE-PHASE ALTERNATING-CURRENT RAILWAY MOTORS

BY A. H. ARMSTRONG

Owing to the success attending the several installations of single-phase alternating-current railway motors in this country and abroad, and the suitability of this type of motive power for the electrification of certain steam lines, the questions have been asked as to whether the 25-cycle frequency thus far universally used is the frequency best adapted for alternating-current motor design and operation, or whether the benefits obtained by the use of a lower frequency are sufficient to justify its introduction. This paper is intended to open a discussion on the relative merits of 25 cycles and a lower frequency, and will touch briefly upon the advantages and disadvantages of the present standard of 25 cycles and any proposed standard of a lower frequency.

All the alternating-current railway motor installations thus far made in this country have employed a frequency of 25 cycles, and, with one exception, the service has consisted of the movement of single-car units at maximum speeds of approximately 50 miles an hour at intervals of one-hour headway over a single-track line. That is, all alternating-current roads have been designed to take care of interurban passenger business with the incidental movement of express matter and miscellaneous freight.

It has been found that the alternating-current single-phase commutator motor can be developed to a commercially successful stage at a frequency of 25 cycles; and although some benefits in respect to weight, efficiency, and commutation are to be obtained with the adoption of a lower frequency, the advantages do not as yet seem great enough to justify the standardization of a new frequency suitable to alternating-current commutator motor operation alone. Recognizing the enormous commercial advantage of offering an alternating-current railway motor which could operate from existing power plants, the manufacturers have perfected alternating-current equipments for interurban service for the standard frequency of 25 cycles already universally in use for this class of work.

The introduction of a new frequency calling for the design and establishment of a complete new line of generating, transmitting, and receiving apparatus is a most serious matter; it should not be undertaken without carefully considering all the factors, both commercial and engineering, entering into the case. With the coming electrification of steam roads there is a demand for motors of increased capacity, and the possible limitations of 25-cycle design in large alternating-current motors of certain types is more keenly felt, hence the inquiry at this time into the question of the proper frequency to be adopted when the alternating-current motor is selected as the type of motive power for steam-road electrification.

The various points to be considered may be classed under the following heads:

1. The effect of frequency on design of motor equipment.
2. The effect of frequency on coefficient of adhesion.
3. The effect of frequency on generating and distributing systems.
4. Commercial considerations.
5. Locomotive design and selection of motive power.

The effect of frequency on design of motor equipment. Taking the weight of a direct-current motor as 100 per cent., it is probable that the values in the following table hold approximately true.

COMPARATIVE WEIGHT OF DIRECT-CURRENT AND ALTERNATING-CURRENT MOTORS

Direct Current	25-cycle alternating current	15-cycle alternating current
One-hour capacity 100	150	130
Continuous capacity 100	125	120

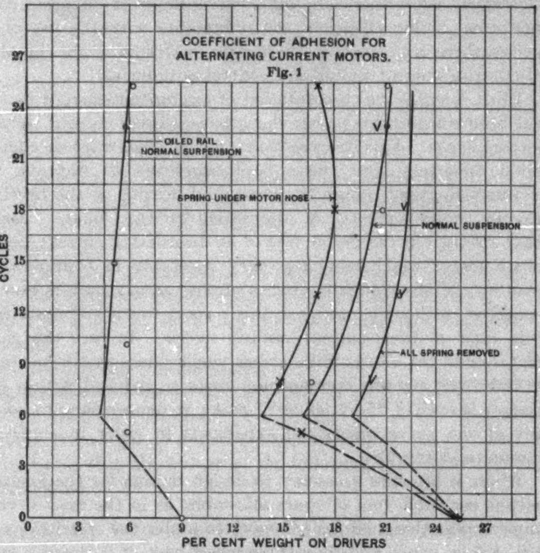
These figures apply to motors designed to give in all cases the same output and heating at the same speeds, but with an admitted superiority in commutation in motors of direct-current commutating-pole design. While the weight of the 15-cycle alternating-current motor is less than that of the 25-cycle motor, this will be partly offset by an increase of 30 per cent. in the weight of the step-down transformer on the car. Although the car transformer weighs but approximately 20 per cent. of the complete equipment, including control and motors, an increase of 30 per cent. in its weight will practically offset the reduction in motor weight when recourse is had to 15 cycles. Therefore, while there are other advantages in superior commutation, higher efficiency, etc., obtaining with the use of 15 cycles, there is no material reduction in weight of the complete alternating-current motor and control equipment.

Until recently the commutation of alternating-current motors has been considerably poorer than that of direct-current railway motors in use. Various expedients, such as high-resistance leads, lower frequency, etc., have been suggested to improve the commutation and reduce the losses and heating at the brushes. Recent improvements in alternating-current motor design have resulted in the production of an alternating-current single-phase motor which compares very favorably in commutation with any of the standard direct-current railway motors now in operation, although inferior in this respect to the commutating-pole type of direct-current railway motor. In fact the commutation of the alternating-current single-phase motor has been so improved and the commutator losses so reduced with a frequency supply of 25 cycles as to make it unnecessary to adopt any of the above mentioned expedients in order to eliminate commutator troubles.

Where it becomes necessary to design motors for the greatest output per cubic foot of space allowable, as in the case of very large motors designed for locomotives under the restrictions of 4-ft. 8.5-in. gauge and reasonable wheel-base, it is possible that the adoption of a frequency lower than 25 cycles permits a greater latitude in design of alternating-current single-phase motors of certain types.

2. *The effect of frequency on coefficient of adhesion.* The torque delivered to the driving-wheels by the alternating-current commutating motor is of a pulsating character, and its effective value is somewhat less than the uniform torque imparted by the direct-current motor. Experiments show that the effective torque is a function of the frequency of motor

supply, and also depends upon the construction of the truck and the method of motor suspension. The values given in Fig. 1, express the relation between tractive effort and frequency for periods from 25 cycles down to zero; that is, direct current. The values given will hold true only with the combination of truck springs, motor suspension, etc., in the test, and the use of stiffer or lighter springs, more rigid or flexibly suspended motor, the use of springs between gear and axle, etc., might give results differing considerably in degree from those submitted herewith.


COEFFICIENT OF ADHESION FOR ALTERNATING CURRENT MOTORS.
Fig. 1

The three curves given represent normal motor suspension, additional spring suspension under the motor nose, and with springs removed, giving practically rigid suspension except for the spring of the armature shaft, gear teeth, etc. While the tests are incomplete, they indicate a slight reduction in the coefficient of adhesion with lower frequency; but so far as can be determined this reduction is not a serious matter in the consideration of 25 cycles or a lower frequency, say 15 cycles.

With normal motor suspension, the coefficient of adhesion as obtained with 25 cycles alternating-current was 82.5 per cent. of the value obtained under the same conditions with the same motor supplied with direct current.

3. *The effect of frequency on generating and distributing apparatus.* The question of generator design at 15 cycles is a serious one and presents many difficulties which can only be partly overcome at an increased cost of the apparatus perfected for 25 cycles. In fact, while certain capacities of low-frequency turbo-generator units may be constructed fairly comparable with 25-cycle units, it is probable that the adoption ot 15 cycles or less would seriously handicap the standardization of a complete line of such units; in any case it will increase the cost of those units which it is possible to construct. The steam turbine has shown itself a most excellent prime mover, and the adoption of 15 cycles is seriously handicapped by the difficulties opposing the successful construction for this frequency of a complete line of generator units of all sizes.

Both step-up and step-down transformers are handicapped at 15 cycles by an approximate increase in cost of 30 per cent. over that of 25-cycle design. This applies to step-up and step-down transformers used throughout the low-frequency system.

4. *Commercial considerations.* Perhaps the benefits of standardization to both the customer and the manufacturer have not been appreciated to any greater extent than in the electric railroad industry. The universal adoption of 25-cycle three-phase supply feeding into the distributing system of railway networks constituted so strong a claim in favor of adopting this frequency when developing the alternating-current railway motor as to outweigh certain known benefits to be obtained with a lower frequency supply. The great field for alternating-current motors of 150-h.p. capacity and less is on interurban lines acting as feeders to the surface, elevated, and subway lines of large cities. The ability of such motors to run from the same alternating-current generating and distributing systems without requiring the introduction of frequency-changer sets constitutes a strong argument in favor of continuing the present practice of installing 25 cycles on such lines.

The type of apparatus adopted for new installations must necessarily be largely dependent upon the apparatus already installed for similar purposes in its neighborhood; it is a question, then, when considering the electrification of steam roads in and about large cities, whether engineers can afford to neglect this principle and cut loose from standards already established and universally used. Furthermore, steam railroad electrification often commences in station and signal lighting and car shops, and 25 cycles is already largely in use for such work. Small motors and transformers are much higher in price at 15 cycles; there is no line developed; and station and car lighting is most unsatisfactory at this frequency.

5. *Locomotive design and selection of motive power.* One of the principle arguments in favor of the electric locomotive is that it permits the concentration of a very large amount of power on the driving-wheels. In this respect the electric locomotive equipped with alternating-current series compensated motors does not compare favorably with other types of motors of both alternating-current and direct-current design. Furthermore, the successful exploitation of these other types of motive power does not demand the adoption of a frequency less than 25 cycles, and hence it is pertinent to inquire if, with our present knowledge of the art, the alternating-current single-phase motor of the series compensated type possesses qualifications which make it so superior to other types of electric motors as to justify the introduction of an odd frequency of benefit only to that one type of motive power. The writer feels much gratified at the success attending the development and operation of the various alternating-current roads already completed, but it should be pointed out that this success has been attained with a frequency of 25 cycles.

Admitting the coming of steam-road electrification, we have not had any demonstration or even convincing figures submitted which would prove beyond doubt the desirability of adopting 15 cycles and the alternating-current series compensated motor to the exclusion of direct-current motors of all types and voltages, three-phase induction motors, or even single-phase alternating-current motors of other types which can be built in large capacities at 25 cycles. In the opinion of the writer it becomes, not the choice of the best frequency for the alternating-current series compensated type of motor, but a question of the proper selection of motive power for the exacting demands of locomotive construction designed for hauling trains of any weight at both high and low speeds over roadbeds of any gradient. The question of frequency might well be left in abeyance until the coming of fuller knowledge of the operation of electric locomotives equipped with motors of different types. Considered from the engineering standpoint of alternating-current series compensated motor design alone, the use of 15 cycles offers advantages in the betterment of commutation, efficiency, and output per pound of motor which may justify its adoption, provided that type of motive power it best suited to the needs of the problem in hand. Taking into account, however, the commercial interests involved, and considering the serious claims that may be advanced in favor of other types of electric motors for which a frequency of 25 cycles is well suited, it appears to the writer that much stronger claims for recognition must be brought forth before the adoption of 15 cycles can be seriously considered.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

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TWENTY-FIVE VERSUS 15 CYCLES FOR HEAVY RAILWAYS

BY N. W. STORER

At the regular meeting of the Institute, on January 25 of this year, a paper was presented by Messrs. Stillwell and Putnam dealing with the electrification of steam railways and referring briefly to the question of the adoption of a standard frequency for single-phase railways. This question aroused a great deal of interest and was discussed at greater length than any other feature of the paper. The authors, while enumerating the advantages of both 25 and 15 cycles, drew the conclusion that the advantages were greatest on the side of the lower frequency, and this opinion was concurred in by most of those who discussed the matter. Many good points were brought out, but all were more or less general; and while it is obviously impossible for the Institute to standardize at this time a frequency for railways using alternating current, a free and full discussion of the matter can hardly fail to produce good results and to furnish more definite information than was available at the time the paper was presented. The arguments in favor of 25 cycles may be reduced to the following:

1. It is a standard frequency which is in use in a great many plants throughout the country.

2. It is probably better suited for general power distribution and is certainly better for lighting than 15 cycles; therefore any railroad having a 15-cycle plant for operating its road would be somewhat handicapped in power for lighting and shop purposes.

3. The higher frequency is better suited for speeds of steam turbines of small size, it being at present uneconomical to build

turbo-generators for less than 2000 kw. at 900 rev. per min., which is the maximum available for 15 cycles.

4. Transformers are lighter and cheaper for 25 cycles.

The principal arguments in favor of 15 cycles are:

1. An increase of from 30 to 40 per cent. in the output of a motor of a given size and a consequent reduction in the total number of motors required to operate a railway, and in the cost of equipment.

2. Better performance of the 15-cycle motors, including higher efficiency, higher power-factor and better commutation.

3. Less dead weight to be carried on cars and locomotives.

4. Lower line losses.

The first argument in favor of 25 cycles; namely, that it is a standard frequency in use in a great many plants of the country, is certainly a good one. It is undoubtedly a very serious matter to consider the introduction of a new frequency for any purpose whatsoever. There are, as is well known, a number of frequencies in use at the present time for which there is no justification except that they are in use, and there is no class of service of which we know that cannot be handled with equal efficiency by one of the standard frequencies, with the exception of the alternating-current railway systems. Railway electrification, if developed as every electrical engineer hopes it will be, will mean an undertaking of such magnitude as to make it practically independent of other electrical interests, so that if a frequency differing from the standards now in use will be advantageous it should be adopted.

The second argument in favor of 25 cycles; namely, that it is better suited for power and lighting purposes than 15 cycles, may be granted without admitting that it is a particularly valuable point. Satisfactory lighting can be obtained with 15 cycles by using a low-voltage lamp having a large filament with high thermal capacity. This will be entirely suitable for ordinary railway lighting. While not having as wide a range of speed as is possible with 25 cycles, 15-cycle induction motors can undoubtedly be used to accommodate practically any class of service required of them. The fact that the single-phase commutating motor is more satisfactory on the low frequency may make the low frequency even more satisfactory for shop purposes than the high frequency. In the discussion of the Stillwell-Putnam paper one speaker called attention to the fact that railway companies would probably sell a large amount of power along their right-of-way to consumers for various purposes, and stated that 15-cycle current would be unsuitable for such service. In reply to this it is only necessary to call attention to the fact that the voltage on any railway circuit is so variable as to make it absolutely unsuitable for lighting purposes, and it would therefore be necessary to introduce a motor-generator set in order to get good results. This might just as easily be made a frequency-changer to supply current at either 25 or 60 cycles, as might seem best for that particular locality. While this unquestionably destroys some of the simplicity of the scheme, it is undoubtedly what would be necessary in order to give satisfactory service, even if 25 cycles were in use on the railway, unless a separate generator were used for the lighting circuits. It seems therefore that the 15-cycle current would be little or no handicap to the railway company in this respect.

The third argument; namely, that the higher frequency is better suited for speeds of steam turbines is undoubtedly true, but it affects a very small proportion of the work. Heavy railroads will require in practically all cases larger generators than 2000-kw. units. In cases where they do not, high-speed turbines can be used and frequency-changers employed. At the same time we must admit that the last word in regard to steam-turbine design has not yet been spoken, and it may shortly be an easy matter to make comparatively small units for use with 15-cycle generators.

The fourth argument, that transformers are lighter and cheaper for 25 than for 15 cycles is undoubtedly true. There will be a difference of probably 25 per cent. in the cost of the transformers for any given service. This difference must be offset by the difference in the cost of the motors.

The meat of the entire argument for the lower frequency is in the greater output of the motors for a given size and weight. It was well shown in the Stillwell and Putnam paper that the cost of car equipments and locomotives would far overbalance the cost of power houses and transformer stations; and while I do not wish at this time to give a mass of estimates as to the saving, I will adhere to the statement previously made that the output from a motor of a certain size will be increased from 30 to 40 per cent. by the use of 15 instead of 25 cycles. This has been proved by tests on several different motors.

A well known 100-h.p., 25-cycle motor operates with full load at a speed of 620 rev. per min., and in the regular one-hour test on the stand has a temperature rise of 89° cent. in commutator and 75° cent. in armature, other parts of the motor being well below 75° cent. Operated at the same speed on 15 cycles, this motor carried a load of 113 h.p. with a maximum temperature rise in commutator of 76.5° cent. and in armature of 72.5° cent. It is safe to say it is good for 115 h.p. with the limiting temperature of 75° cent. in armature. This same motor with a larger number of turns on the field and run on 15 cycles carried at the same speed of 620 rev. per min. a load of 135 h.p. with a temperature rise in commutator of 76° cent., in armature of 75° cent., and in field-coils of 76.5° cent. It is quite safe to rate this motor at 135 h.p. on 15 cycles.

A larger motor carried a load of 255 h.p. with a temperature rise of 71° cent. in commutator and 76° cent. in armature, other temperatures being well below 75° cent. This motor, operated at the same speed under identical conditions on 15 cycles with a load of 300 h.p., rose 73° cent. in commutator and 81° cent. in the armature. With new field-coils having more turns, the motor will carry at least 325 h.p. and probably 340 h.p. with a rise in temperature not exceeding 75° cent.

While these results are all based on the one-hour test, the continuous capacities will have the same increase on 15 cycles. The inference to be drawn from these results is, of course, that the temperature rise being the same for both frequencies, the losses must be approximately the same; and since the output is greater on 15 cycles, the efficiency must therefore be much higher. Further, the tests are all based on 25-cycle motors modified only in field-coils. If the motors are designed especially for the low frequency, the results will be still better.

A comparison of the weights of car equipments for 25 and 15 cycles indicates that there will be an advatnage in favor of the lower frequency, even with the same number of motors. For instance, a four-motor equipment of 100-h.p., 25-cycle motors, with oil-insulated transformer, will weigh approximately 30,000 lb. Such an equipment for 15 cycles would weigh approximately 28,500 lb. The difference is small, but it is in favor of the lower frequency. If two 15-cycle motors of 200 h.p. each, such as are now building, be furnished, the weight of equipment will be reduced to approximately 23,000 lb., or a reduction of 23 per cent. in the weight of the car equipment. While it is perfectly practicable to furnish two motors for a 400-h.p. equipment for operation on 15 cycles, it will be necessary to furnish three or four motors for 25 cycles on account of the great increase in the size of the motor. It is therefore absolutely necessary that the 25-cycle equipment weigh considerably more than that for 15 cycles. In the case of smaller motors aggregating 280 h.p. it is possible to furnish a two-motor equipment operating on 25 cycles. There would, however, be a difference in weight of at least 1500-lb. in each motor in favor of the 15-cycle equipment of the same capacity. This would offset the increased weight of the 15-cycle transformers by at least 1000 lb. In every case, therefore, even where the same number of motors are in use for both frequencies, the 15-cycle equipment will be lighter. On account of the smaller motors the motor trucks will also be lighter, the amount of saving here depending upon the size of the motor.

The greatest gain from the use of 15 cycles is to be found in heavy railroading where locomotives are used. In building locomotives it is desirable, on account of the weight, cost, and maintenance charge, to concentrate the power in as few motors as possible consistent with weight on the drivers and the tractive effort desired. We have found that in virtually all cases the weight of useful apparatus on the drivers, even with 15 cycles, is sufficient to give the necessary adhesion without adding dead weight; therefore the use of 15 cycles means that in practically all cases for the locomotive a smaller number of motors can be used than is possible with 25 cycles. It is frequently the case that three motors which are sufficient with a certain size of driver for 15 cycles would have to be replaced by four motors having the same dimensions. It would sometimes happen that three motors necessary for 25 cycles could be replaced by two of the same dimensions for 15 cycles. In the case of locomotives of very high-speed the extra weight entailed by the use of higher frequency motors, and consequently heavier mechanical parts, would increase the weight of the train to such an extent as to call for a considerably larger output from the motors, simply to haul the extra weight. Such a case we have in mind in a high-speed passenger locomotive that has recently been built.

This locomotive is designed to haul a 400-ton train both on heavy grades and at high speeds on a level track. The locomotive as built for 15 cycles weighs approximately 140 tons, and has four motors each with a nominal rating of 500 h.p. With a 400-ton train behind it, this locomotive would thus have to handle a total of 540 tons. A 25-cycle locomotive built to handle a 400-ton train at the same speeds and on the same grades would require six motors of approximately the same dimensions, and these extra motors together with the extra weight of mechanical parts would bring the total weight of the locomotive up to approximately 185 tons. The total weight of train would thus be 585 tons, or an increase of about 8 per cent. The capacity of these motors would be in the neighborhood of 375 h.p., which would be just about sufficient to handle the extra weight. It must be seen at once that the motors for this locomotive would cost 50 per cent. more and the mechanical parts also considerably more. The only parts of the equipment which would cost less would be the transformer and preventive coils, and the control equipment would be enough more expensive to counterbalance this.

In this connection it may be of interest to give a brief description of the locomotive as built. It is of the articulated type, each half of which has two pairs of drivers and a four-wheel truck similar to the standard American type of steam locomotive, the two halves being coupled back to back. The drivers are 72 in. in diameter with 7 ft. 6 in. between centers of axles. On each axle is mounted a gearless motor having a nominal rating of 500 h.p. and a continuous capacity with forced ventilation of about 375 h.p. The motors, weighing approximately 19,500 lb., are spring-supported, mounted, and connected to the drivers in exactly the same way as the motors on the single-phase locomotive for the New York, New Haven & Hartford Railroad. This feature has been described so many times that it is unnecessary to repeat it. The frame of the locomotive is of the standard steam-locomotive type placed outside of the wheels. It is of cast steel connected at the front and rear and at three places between the ends by heavy cast-steel girders. The truck, which is of the standard steam-locomotive pattern, has 36-in. wheels, with a wheel-base of 6 ft. 2 in.

The electrical and other equipment in the cab is mounted on a raised platform which is about 2 ft. above the floor-line and occupies the middle of the cab, allowing for a passageway on either side. There are numerous windows along the sides of the cab which afford excellent light for the inspection of the apparatus. The equipment is extremely simple and accessible. The main transformer, which is designed for 11,000 volts, is mounted above the truck, with the top just below the platform in the cab. Directly above the transformer is located the electropneumatic switch-group to which the various taps in the transformer are carried. Back of the switch-group are the preventive coils used in passing from step to step on the transformer, and from these preventive coils runs a single lead to the reverser switch-group, which is placed directly above the main motors. On this raised platform are also placed the motor-driven air-compressor, the motor-driven blower for furnishing air for ventilation of the motors and transformer, and the air reservoirs. Suspended from the structural work between the platform and the Z-bars in the roof of the cab are the oil circuit-breaker in the high-tension circuit leading to the transformer, the small switches used in connection with the auxiliary motors, and the 20-volt battery which is used for operating the valve-magnets in the controller. The high-tension current is collected from the overhead wire by the standard type of pantagraph trolley. On account of the large drivers and the comparatively high position of the apparatus in the cab, the center of gravity of the locomotive is higher than is usual in electric locomotives. The riding qualities of the locomotive are exceptionally good. The weight of the locomotive, as stated, is 140 tons, there being 50,000 lb. on each driving axle and 40,000 lb. on each truck.

In the case of geared locomotives for heavy freight service, there is still the advantage in favor of 15 cycles. Where the same number of motors is used for both frequencies, it will be necessary to use larger wheels for the 25-cycle locomotive. Low-speed locomotives are especially at a disadvantage with 25 cycles. It is possible to make a geared motor with a capacity of 400 to 450 h.p. for slow-speed freight service with 15 cycles, while with 25 cycles a 300-h.p. motor is as powerful as it is practical to use. This means that in the freight service there is virtually the same condition as in passenger service; namely, that about one-third more motors will be required to perform the service. The locomotive will weigh from 10 to 35 per cent. more.

An examination of the efficiency curves for 15-cycle motors compared with those for 25 cycles will show differences in the losses in the motors alone which will mean a considerable difference in the capacity of the power station. This, when added to the power required to haul the extra weight, and the increased line-loss due to the higher frequency, will make a difference of from 5 to 15 per cent. in favor of the 15-cycle equipment. Without giving estimates or long tabulated statements, I leave it to the judgment of the members of the Institute to decide whether it is not advisable, with these facts in mind, to recommend a new frequency.

It is well known that when the advent of the first successful single-phase railway motor was announced by Benj. G. Lamme in his historic paper before the Institute in 1902 the frequency which he advocated was 2000 alternations per minute, or 16⅔ cycles per second. It was believed at that time that this frequency was best suited to meet the many requirements of power plants for railway apparatus. However, owing to the experimental nature of the undertaking, it was deemed advisable to use the standard frequency of 25 cycles until the commercial success of the system was assured. At the same time it was realized that the practical difficulties to be overcome in the single-phase system would be much greater with the higher frequency. Moreover, in the first equipments sold the motors were of comparatively small size, so that the space occupied by them was not limited. Furthermore, the number of motors in an equipment was fixed by conditions other than dimensions and weight, four-motor equipments being selected in nearly every case, partly on account of the prevailing fad for four-motor equipments and partly because most of the equipments were built for operation on both alternating current and direct current. At any rate, aside from the greater difficulties met with in the design of the high-frequency motor in order to get good performance, the question of frequency was of comparatively small importance. Since that time some 15 or 20 roads have been put in commercial operation with single-phase current at 25 cycles. It has been proved beyond doubt that the single-phase motor is a thoroughly practical and commercial machine. At the same time, as was anticipated, all our experience goes to show the advantage to be gained by the use of a lower frequency. This frequency need not be fixed at exactly 15 or 16⅔ cycles. As far as the motor operation is concerned, a variation of one or two cycles either way will have comparatively little effect; but we believe, for the sake of using proper ratios between this and existing frequencies, that 15 cycles, which is one-fourth of the standard 60-cycle frequency, or 16⅔ cycles, which is two-thirds of the standard 25-cycle frequency, should be adopted for use, especially on heavy railroads. While this will undoubtedly make it necessary for the manufacturing companies to keep a larger variety of apparatus in stock (as there is no doubt that 25-cycle railways will be operated for a long time to come) the advantage to be gained from the lower frequency in the wider use of apparatus will far outweigh any slight disadvantage of this kind.

The mistake made by the blacksmith when he made the template which fixed the gauge of the standard railways at 4 ft. 8.5 in. is a matter of tradition. It is recognized as being one of the most far-reaching mistakes ever made, inasmuch as it has ever since placed a limit on the capacity of the railroads of our country, both by limiting the capacity of steam locomotives and the size of cars, and last but not least, the capacity of electric railway motors and locomotives. What an enormous benefit would be gained from even a paltry increase from 4 ft. 8.5 in. to 5 ft. What powerful machines could be built for a gauge of 6 ft.! But the mistake has been made, and it will cost so much to rectify it, that the boldest of our railway magnates is staggered by the suggestion.

Electrical engineers have an enormous responsibility in deciding upon matters of detail, such as frequency, which will have an effect that will far outlast anyone who has a voice in the matter; and it certainly behooves us as engineers to consider carefully before recommending the continuance of the present standard frequency of 25 cycles, where it imposes such a handicap on the capacity of our transportation systems.

DISCUSSION ON "THE CHOICE OF FREQUENCY FOR SINGLE-PHASE, ALTERNATING-CURRENT RAILWAY MOTORS", AND "TWENTY-FIVE *versus* FIFTEEN CYCLES FOR HEAVY RAILWAYS", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

H. G. Reist: With engine-driven generators the problem is a comparatively simple one, since not much difficulty is experienced in building machines for 15 cycles. The cost of the generators will be increased somewhat, perhaps 30 per cent. With turbine-driven generators the increased difficulty is very much more serious. As has been pointed out by one of the speakers, in smaller size generators, about 2000 kw. capacity, the increase of steam consumption on account of the limit in speed becomes serious, and undoubtedly there will be many places where generators of that size, or smaller, will be needed for long distance railway work. On larger sizes, the speed is more favorable for the turbine, but the generators have to be built with two poles only, which makes it a difficult designing problem. The machine becomes massive, the magnetic circuits become exceedingly long, and the weight of the machine must be greatly increased over that of the 25-cycle machine. Roughly, probably the weight and the cost would be increased fifty per cent. over a similar 25-cycle machine. The efficiency would also be a little less, although that is probably not a very serious matter; it might be one per cent. less at full load than with the higher frequencies.

C. W. Stone: If the design of turbine-driven generators is to be complicated by a combination of lower frequencies and single-phase operation, the generator becomes almost prohibitive unless 450 revolutions instead of 900 are used on the large capacity machines. On machines of 8,000 or 10,000 kw. capacity, 450 revolutions is very bad from the steam end. All the recent 25-cycle machines of large capacity have been run at approximately 750 revolutions. To increase the speed from 750 to 900 rev. per min. and make the generator both single-phase and 15 cycle is not to be considered.

E. J. Berg: While I do not believe that it will be necessary to resort to a frequency lower than 25 cycles, I think that some of the objections raised against the lower frequency are not well taken. A so-called half-frequency generator was invented several years ago, a generator with a given number of poles giving half the frequency of the regular generator operated at the same rotative speed. In construction, this generator was similar to the induction motor; in its action, to the well-known frequency-changer. Instead of exciting the field by direct current, alternating current of a given frequency was used, and the magnetic field made to rotate in the same direction as the armature but at half its speed. By this scheme, the frequency corresponding to one-half the speed could be obtained, not only from the stationary, but from the revolving member. Obviously, the exciting current had to be delivered at the lower frequency, but this was not objectionable, as the actual power supplied was slight and therefore the inefficiency of the low-speed turbine of little consequence.

L. B. Stillwell: I am much pleased to find a question of such transcendent importance as this, of the best frequency for railway work, receiving the serious consideration of the engineers of our manufacturing companies.

The electric railway fraternity now for the first time is undertaking the electrification of railways operating heavy traffic and employing steam locomotives. This work presents a problem more important commercially than any we have hitherto attacked. We are dealing with people who are not of the type that we had to deal with in the early days of electric lighting. The railways of the United States are managed by men whose education in most instances is largely an engineering education. They have their own excellently prepared and thoroughly experienced engineering staffs who will pass upon these questions. Therefore, it is of especial importance in considering such questions as this, that we should take a broad view, saving money for our clients by fighting out differences of opinion on paper and on the floors of these conventions, and, if possible, agreeing among ourselves upon all necessary fundamental standards.

The paper which Mr. Putnam and I had the honor to present before the Institute in January last, raised this question of frequency in railway service. Our feeling was that a mistake in all probability was being made. The figures which we worked out were intentionally broad, probably broader in application than any we shall see in our time, but it seemed advisable to look at the entire railway field and attempt to realize the magnitude of this problem. We therefore followed out our analysis of the comparative costs of operation, by figures showing the total cost of electrifying the railways of the United States. Some of the technical journals, whose specialty is steam railway practice, have ridiculed the idea of considering even the possibility of the electrification of all the steam railways in the United States. Probably no one here expects that this will be done in the near future, if ever; but it is significant to find that if we consider the average railway in the United States upon which there are but seven trains in each direction per day and apply to its operation single-phase alternating current, using a transmission voltage equal to that which is to-day in use transmitting power from Niagara Falls to Rochester and Syracuse, it would be possible to save approximately 18% of the present operating costs. This conclusion has not been assailed in respect to anything that is material. Even if we admit every exception to our total figures which was noted in the discussion, we still have a saving of at least 15%. This is a very important and a surprising fact. It indicates not that all of the railways in the United States will be electrified in the next ten years, but it does indicate strong probability of a more rapid extension of the application of electricity to the operation of trunk-line systems than has been generally realized, even by electrical engineers.

In calculating the reduction in operating costs, it is hardly necessary to say that we recognize also what several of our critics have kindly pointed out; namely, that the principal object in view, when the management of a railway decides to electrify its lines, is not reduction of operating expenses but increase of earning power. This fact is well known and has been referred to in many previous papers and discussions. The two reasons undoubtedly constitute an argument operating powerfully to induce railway electrification. The point which I wish to emphasize is that this electrification is in all probability coming at a rate which greatly emphasizes the importance of early standardization of everything essential to interchange of traffic.

A recent bulletin of the Census Bureau of the United States, prepared by Mr. Martin, shows that from 1900 to 1905 the products of companies manufacturing electric apparatus were more than doubled. In the year 1900 few would have dared to predict such an increase.

When we take the broad view and realize the probability of a more rapid extension of the use of electric equipment in trunk-line railway service, the suggestion that it is of utmost importance to adopt a standard frequency especially adapted to this work appears less radical than it does to the factory engineer who is interested primarily in the problem of designing a complete line of turbo-generators.

The total cost of electrifying a railway, is in general not less than $200 per kilowatt of generating capacity installed, and in considering the effect of 25 versus 15 cycles the difference in the cost of the average turbo-generator might easily be $5 one way or the other without materially affecting our conclusion. Moreover, in dealing with the problem of trunk-line electrification we may as well throw aside all of the smaller generators, as this service will rarely, if ever, call for a generating unit of less than 3000 kw. A single freight train, such as is hauled over some of our trunk lines, would require one 3000-kw. generator.

There is another field the limits of which, while not clearly defined, are sufficiently understood; that is, the interurban. Much argument has been presented at various meetings of the Institute this year bearing upon the question of the possible use of a 1200-volt direct-current system as a substitute for the high potential alternating-current system. This system, perhaps, has its field in the interurban service. I think it can have no proper application in the broad service of trunk-line railways of which I am speaking. A potential of 1200 volts on the trolley or third-rail will never be satisfactory for the operation of freight trains. We must go radically higher. Anything less than 6000 volts in single-phase service is out of the question, and the question for us to decide is: " What frequency shall be adopted for alternating-current railway operation "?

The paper which Mr. Storer has read is one of the exceptionally valuable papers of the year. It contains precisely the kind of information which is needed in dealing with the very important question of frequency; and a half dozen pages of facts, such as he has given us, are worth any number of pages of general speculative opinion. In the discussion of my paper in January, the engineers of both the great manufacturing companies engaged in single-phase work, who had to do with the design of the motors and their application to trucks within the limits of space available, testified unanimously to the effect that at given cost 15 cycles secures one-third more draw-bar pull than does a frequency of 25 cycles. The people who will buy electrical apparatus to equip trunk-line railways will buy draw-bar pull. Recognizing this, it seems to me that we must recognize also the fact that, in view of the evidence set forth in the Institute papers and discussions this year, 15 cycles should be adopted in general for heavy railway work. I do not mean to say that a resolution to this effect should be passed, but I do say that unless evidence in favor of 25 cycles not hitherto presented can be brought forward, 15 cycles should be chosen by consensus of sound engineering opinion and should be introduced into practice as promptly as possible.

At the meeting in May when Mr. Sprague's paper was read some interesting facts were brought out in the discussion, especially the statement that one of the great manufacturing companies since January had produced a new single-phase motor of remarkable characteristics which operated substantially as well at 25 cycles as at 15 cycles. This is a very interesting statement, and it suggests information which I hope will be promptly and conclusively disclosed because some of us in the consulting field are now confronted by the problem of frequency for railways which at the present time are considering only the equipment of a terminal or a short division, but which by reason of the saving effected in operation and of increased earning power are morally certain to extend that electrification over much greater parts of their existing systems.

W. N. Smith: I cannot escape the conclusion that the question of electrification of steam railroads is so extremely broad that, as has been indicated by both Mr. Storer and Mr. Stillwell, we should not deliberately tie ourselves down to any existing commercial frequency which was developed primarily for lighting and stationary power.

If the steam railroads want draw-bar pull, which is unquestionably what they need to get the maximum amount of tonnage over a given track in a given time, they will not wish to be handicapped by the facilities offered by some local power company, no matter how large it may be, which may have 25 cycles to offer, if 15 cycles is going to be the best thing for them to use. Great as is the power development here at Niagara Falls, I doubt if there would be enough 25-cycle power generated to supply the commercial demands of this region, now developing so rapidly, and at the same time supply the railway power required by such wholesale electrification as it is conceivable that large railway systems might eventually undertake. I do not believe that there is sufficient power capacity at present installed in any one plant anywhere in the country which would justify the undertaking of the wholesale electrification of a large steam railroad in its own vicinity, in addition to its own commercial load. It appears to me that the problem will without doubt result in the railway companies either having their own power stations, and getting developed for themselves the kind of machinery that they need the most, or calling into existence commercial power companies which will do it for them, developing coal mine power or large water power in such units and by such methods of distribution as the railway companies, their biggest customers, may demand.

William McClellan: If we examine these papers carefully, we shall find a decided agreement between the two authors as to facts, though the opinions and conclusions given are somewhat different. Apparently there is no uncertainty as to the weight-efficiency. Variable adhesion is eliminated as having no practical bearing. As far as the difficulty of generating 15-cycle power by turbines is concerned, Mr. Berg has anticipated me. We had a paper a year or two ago on a type of generator excited with alternating current. It was suggested that such a machine could be built self-exciting, in our case for 15 cycles, and run at double speed, thus making it possible to drive it efficiently by a turbine.

Apparently, the chief argument against 15 cycles is the difficulty of changing present commercial standards; this is certainly entitled to most serious consideration. Nevertheless, it should not be forgotten that great advances have been made in the past by discarding what seemed at the time as fixed practice. This was one of the arguments against the adoption of the metric system. Notwithstanding this, it was announced a few days ago that the Baldwin Locomotive Works had built a locomotive with its regular workmen and had used the metric system throughout. The engineers and workmen were well pleased with the system, and the arguments against its adoption were apparently refuted.

It has also been stated that a low frequency would not be suitable for other purposes than motive power. In this connection it should not be forgotten that it is probable that large lighting and power loads will not be worked from the same busbars as traction loads. It is also worth noting that the present tendency of economic progress is to limit transportation companies strictly to the transportation business, and it is not likely that they will go into the business of selling power. Lighting and power for their own shops, stations etc., is relatively unimportant.

The important point noted in the Stillwell-Putnam paper was that the cost of the motive power equipment is by far the greater part of the expense of electrification. This brings us directly to the motor and its efficiency.

A short time ago there seemed to be a decided unanimity of opinion that the compensated-field single-phase motor was the type which the manufacturers had found to be most advantageous. It was expected that it would be greatly improved but the type would remain standard. With this motor, much would be gained by using 15 cycles. The engineer with the facts before him, and if not limited by local considerations, would necessarily hesitate a long time before refusing to adopt this motor.

Recently, however, we have had public notice that another type of motor is developing rapidly and is said to be nearly as good as the direct-current motor without commutating poles. From the standpoint of both weight and efficiency, this motor will perhaps not offer increased advantages when adjusted to a circuit of lower frequency than 15 cycles. If so, the whole matter is uncertain, and it would be exceedingly unwise to make any decision whatever until we have more definite information in regard to this motor.

It is worth repeating that the whole argument centers around the motor, or motor capacity, if you will, and no decision should be made to standardize frequency until the type of motor is standardized first.

Chas. P. Steinmetz: Probably the railways will generate their own power. At the same time it is a serious matter to depend on one power house only, or even two power houses, and if in an emergency power can be derived from some other station it is a great advantage.

The amount of power which would be required by the steam railways after electrification is frequently vastly overestimated. I understand some investigation on this subject has been made by Mr. Ferguson of Chicago, which I hope will be communicated later.

I believe the conclusion was that if all the railways entering Chicago received their power from Mr. Ferguson's steam-turbine station, the railway load would by no means be the largest load on the system, but probably within the overload capacity of the station.

The question before us is: first, whether the adoption of the lower frequency is necessary; secondly, whether this lower frequency should be 15 cycles or any other frequency. At present we have two standard frequencies, 25 cycles and 60 cycles, but the spectres of sundry other abandoned frequencies still haunt the electrical engineer—125 cycles, 133 cycles, 50, 40 and 30 cycles. It appears to me, and probably to everybody who remembers and still sees the difficulties due to the existence of these odd frequencies, that it would be disastrous to introduce another frequency and then after a year or so find it was not necessary and have to abandon it. Therefore, we should be extremely careful to see whether a lower frequency is necessary. If it is necessary, which frequency should be chosen?

I do not believe 15 cycles is a suitable lower frequency. If we have to use a lower frequency it would be because the alternating-current railway motor is practically inoperative, at least in larger units, at 25 cycles. If that is the case, then 15 cycles probably is not yet the most suitable frequency; but the most suitable frequency is far lower than 15 cycles, and 15 cycles would perhaps be a compromise frequency. The experience of compromise frequencies and compromise designs has been disastrous, and would better not be repeated. If it seems wise to adopt lower frequencies, we should probably have to adopt not 15 but 12.5 or even 10 cycles.

In considering lower frequencies we must realize that, with the single exception of the series alternating-current motor, every part of the system, from the steam turbine generator to the incandescent lamp lighting the cars, the lower frequency is a handicap. This brings us to the need of a lower frequency. We must consider that every type of electrical apparatus has a frequency at which its design is most economical, most satisfactory, and most reliable. For small apparatus usually a somewhat higher frequency and for large apparatus a somewhat lower frequency is best suited. For instance, economically the most efficient frequency for the induction motor is 40 cycles; as a result, induction motors are built for 60 cycles or 25 cycles, both frequencies being sufficiently near the economical frequency for practical purposes. The 60-cycle frequency is mainly used with smaller motors, and 25 cycle with larger motors; and the maximum economy for smaller sizes shifts upward, and for larger sizes downward in frequency.

In the transformer we find the maximum economy is beyond the commercial frequencies. The 125-cycle transformer is better and more economical than the 60- or the 25-cycle transformer. Where the maximum economy lies we do not know; there must be some definite frequency, because we know that the alternating-current transformer is not well suited for 10,000 cycles; it is difficult to design; not economical; that is, 10,000 cycles is too high a frequency, but within the range of available frequencies, the higher the frequency the better for the transformer.

The maximum economy of the synchronous converter is at 25 cycles. A converter designed for a frequency higher than 25 cycles, or lower than 25 cycles, is, as a rule, inferior to the 25-cycle converter.

In the alternating-current series motor the maximum economy is at the lowest possible frequency; the lower the frequency the better the motor. The best series alternating-current motor would be the motor designed for zero frequency; that is continuous current. In that, I agree with Mr. Sprague. In any other apparatus, the larger the size the more urgent the need of lower frequency, and, while good results have been obtained with 25 cycles on moderately small motors in interurban service, for large units, as heavy locomotives, 25 cycles seem almost impracticable for the series alternating-current motor.

It is evident then that the frequency must be lowered so as to approach that of maximum economy, or the type of the motor must be changed. There is no reason to assume that the series motor is the final development of electric railroading. I have really never felt satisfied that the series commutator motor is the solution of the problem and have repeatedly said so. There are other kinds of motors in which the maximum economy is not at the minimum frequency, but is, as near as we can judge at the present time, not far from 25 cycles. If then we adopt the lower frequency, we might find that we have handicapped ourselves in designing alternating-current commutator motors of different types.

Mr. Ernst Alexanderson has succeeded in devising a type of motor in which it appears that the maximum economy of the alternating-current commutator motor is not at zero frequency but probably is in the neighborhood of 25 cycles, and for this motor that would be the best frequency. In this respect, I disagree with Mr. Armstrong in the data on the relative comparison of 25-cycle and 15-cycle motors. I believe that his statements rather represent a period which is past, but still influenced by the experience with the series motor. As far as our present experience goes, the two frequencies, 25 and 15 cycles, in railway-motor design at the present time seem to be equal in economy, and for all I know 25 cycles may be the better frequency. That necessarily means that 15 cycles has no right to exist.

The great and only difficulty with the alternating-current motor is the commutation; all other troubles are secondary, and merely results of the limitations imposed upon the design by the attempt to make the sparking at the commutator least destructive. During the operation of the motor electromotive forces are induced in the short circuited coil under the brush, which lead to more or less disastrous sparking and heating of the commutator, destruction of the brushes, energy losses by parasitic currents, etc. To reduce this effect we can either reduce the electromotive forces induced in the short-circuited coil, by reducing the frequency—and that is after all the gist of the desire to lower the frequency: to get lower electromotive forces induced in the short-circuited coil at commutation—or we can attempt to reduce the currents produced by these electromotive forces by inserting high resistance commutator leads. This is beneficial to some extent, although it introduces the great difficulty to protect these high resistance leads against self-destruction by excessive local heating. But the benefit is limited, because while we reduce the current the insertion of resistance raises the voltage. The solution of the difficulty is to modify the type of the motor so that no electromotive forces are induced in these short-circuited coils, and that is what Mr. Alexanderson has done and concerning which I believe he will give us a paper in a very short time.

Peter Junkersfeld: Considering passenger trains only, and assuming for the sake of argument that it would be physically possible to electrify all the steam railroads centering in the city for a distance of 25 miles from the respective passenger stations, within the next year, we have estimated that the total power demanded by these various railroads would probably not exceed 20 per cent. of all the power generated in Chicago by all the various companies. This figure of 20% would even then be true only for the next year. After that, the proportion of power demanded by the steam railroads would decrease, due to the fact that the amount of power required for all other purposes increases in a much faster ratio. The large amount of industrial power and the very large amount of interior lighting not yet supplied electrically and that still to be developed in Chicago would justify the opinion that at the end of five years the total steam railway demand would not exceed, possibly would be less than ten per cent. of the total electric power generated in the city. This applies to Chicago and to the railroads for a distance of 25 miles radiating outward from their passenger terminals, so that, as Dr. Steinmetz has said, the proportion of power which will be demanded by the electrification of the steam railroads is not nearly so much as we might imagine.

Gano S. Dunn: How would it work out if freight were included ?

Peter Junkersfeld: We made no calculations on that, and it is a hard thing to estimate.

The most optimistic speakers on this subject of railway electrification have said that they hardly expected to see all of the railways electrified within their lifetime; in other words, it is largely a problem of the next generation. We all agree that we should look out for the next generation, but in doing so we should not neglect the present. The electrification of steam railways at and near their terminals, however, is particularly important, in fact that problem is a live and pressing one now.

In the electrification of such terminals the question of direct current or alternating current has by no means yet been settled. There is still a great deal of controversy on this point, and the probabilities are, in my mind, that ultimately the direct current will perhaps be largely used in electrifying terminals. This does not apply to the electrification of long steam railroad lines, trunk lines, etc., but it does apply to the electrification of terminals, not only because of the present state of the railway motor art, but also because of agitation against overhead high tension wires and things of that sort particularly in large cities.

We seem in this country to be passing into an era in which public regulation will perhaps have quite a great deal more effect on electrical development than in the past, and we are confirmed in that impression if we observe the experiences in other countries. In many of these, the electrical development has not been so great as in this country, not because they are less ingenious, but because they have had certain handicaps. These handicaps may appear here, there is already some evidence that they will appear, and may work somewhat against the operation of terminals with high tension overhead trolleys, but may not work against future similar single-phase operation of the long railway lines.

Coming now to the question of power supply for terminals, and even admitting for the moment that possibly single-phase motors could be used for that purpose, we should be extremely careful before recommending an odd frequency, because on the crowded tracks of the terminals the question of reliability and continuity in moving the trains is of primary importance; of much greater importance than the moving of the trains between the large cities. In order to secure the best results it should not only be possible for the railway companies to buy power, when this can be done more economically, but at least to be in a position to readily interchange power with other power supplying companies. Otherwise, the railroad companies will have to make large investments in reserve power equipment to protect their business. The greatest factor in economical electric power generation is a diversified demand, which means a very large number of peaks, and as a result non-coincident peaks. One of the greatest factors in electrical development in a community is low cost of electric power. That can only be secured in the ultimate by having an arrangement so that the interchange of power can be made readily and quickly between the different power consuming systems whether owned or operated by one or by several companies.

The selection of the frequency for any given service should be based on the predominating demand. In a number of the larger cities in this country the predominating demand has been in favor of 25 cycles. That condition still exists to-day, and Dr. Steinmetz has told us that for synchronous converter work, which is 75 per cent. at least of the total demand in three or four of the larger cities, that 25 cycles is the best frequency. For that additional reason, we should be careful before recommending any odd frequency if we want to conserve the best interests of the various companies or clients we represent.

Henry G. Stott: I think that the question of supplying power for railroads has been looked at from a slightly different standpoint than it is by those who are accustomed to the conditions obtaining in most of the large companies that are developing their own power. I wonder which power plant in the United States could give an emergency supply equal to 25% of its rated capacity. Railroad plants and lighting plants have to be designed for a peak load. In a lighting plant the peak load will last not to exceed 400 hours per annum. That means an enormous investment for a short time. The railroad plants have practically a peak load of from 800 to 1000 hours per annum. How can we expect either our lighting plants or railroad plants to carry a reserve of 25% above their peaks for the purpose of guaranteeing a supply to anyone else, and if they do it, at what price can they do it?

The question seems to me to be one which will be solved by the location of a number of plants along our railroad lines. These plants will be able to give a much more reliable service, which, after all, will ultimately be the criterion applied by everyone to the question, rather than the cost. Imagine, for example, a transmission line from Niagara Falls to New York, and our railroads depending upon it, and subject to every thunder storm that comes up. I have no data at hand to show what the average interruptions of such power would be, but I know this—it would be greatly in excess of the interruptions which would obtain in a number of smaller plants distributed along the line. In other words, we can get better insurance by carrying our power in the shape of coal on freight cars than we can by carrying the power on high-tension wires. The insurance given by a number of distributed plants is going to be infinitely greater than we can obtain in any other way.

A. H. Armstrong: From the discussion it would appear that certain advantages in motor design can be taken advantage of at 15 cycles which are not possible with higher frequencies. The problem now becomes one of weighing possible advantages of motor construction against the handicap of using 15 cycles for the generating and distributing system, and seeing if these advantages are sufficiently great to warrant the introduction of an odd frequency with all its engineering and commercial complications. The history of alternating-current distribution has been a constant tendency toward the adoption of lower frequencies as the demands of new apparatus became pressing. Up till now the question of low frequency has been governed by the performance of converters. A frequency of 25 cycles has been sufficiently low to satisfy all the needs of the situation. With the advent of the alternating-current single-phase motor, we have a type of apparatus calling for low frequency, but the greater advantages of 15 cycles must be great indeed to warrant a departure from the standard 25 cycles now in universal use, especially as the single-phase motor is not in any sense inoperative at the higher frequency. It is not a question of the adoption of 15 cycles in order to make alternating-current motor installations possible, as the recent inventions of Mr. Alexanderson and others have given us a motor which is thoroughly commercial at 25 cycles.

I agree thoroughly with Mr. Junkersfeld that the electrification of steam railroads is not to be considered entirely from an alternating-current standpoint, and, instead of steam road terminals presenting a problem calling for a change in the frequency of supply in order better to accommodate the limitations of alternating-current motor design, I would suggest that this class of railroad electrification presents a problem of alternating versus direct current with a decided preference for direct current.

While recent improvements have made the alternating-current motor a thoroughly commercial piece of apparatus with a frequency supply of 25 cycles, due weight must be given to the further consideration that any continued development of this type of apparatus must show further improvements which will make 25 cycles still more desirable; in other words, having a successful 25-cycle alternating-current motor to-day, we can look to the future with the confident hope that any continued development will still further minimize any possible advantage which 15 cycles may enjoy over 25 cycles. At such a short period as two months ago, it appeared that a frequency of 15 cycles was necessary in order to make possible the construction of large alternating-current single-phase motors giving good commutation. The improvements made in two months, however, have made the adoption of 15 cycles less attractive, and it is fair to assume that we have not heard the last from alternating-current motor designers and that the future holds bright promise of still further developments. If we can get a motor just as good at 25 cycles, or even nearly as good, there is no reason to adopt low frequency. In fact, there is every reason to adhere to a frequency so universally in use as 25 cycles.

N. W. Storer: I have only a few words to say in conclusion. Mr. Steinmetz raised the point in regard to suitability of 15 cycles for railway work. He insists that the lower the frequency the better the motor will be. On this point, I cannot agree with him. There is much more to be considered in building a single-phase motor than simply to reduce the short-circuit current to a minimum and thus obtain good commutation. If the frequency is reduced much below 15 cycles, the pulsations of torque will cause considerable trouble. Everything considered, I regard 15 cycles as the best frequency for railway purposes. It is a simple matter to obtain very satisfactory commutation in a 15-cycle single-phase motor. Within the last few days we have been testing the locomotive of which I speak and I have seen the motor carry 100 per cent. overload in current for several minutes at a time when hauling a train with the brakes set, and there was practically no sparking at the commutator, the commutation being much better than almost any of the standard direct-current series motors could do under similar circumstances.

So far as commutation is concerned, we have not regarded that as the main reason for recommending a lower frequency than 25 cycles for railway work. Our desire has been simply to increase the capacity of the motors. If this Alexanderson motor which has been mentioned by so many speakers is able to give the same capacity at 25 cycles that the compensated series-wound motor gives at 15 cycles, I should say by all means stick to 25 cycles, unless there are some other defects in the motor of which we are not aware. No one wishes to add another to the standard frequencies any less than I do. We should cling to the standards as far as possible. I believe that, if in future development it is found that the installation of 15-cycle current for the electrification of a large system can be done more cheaply and operated more cheaply than the same work can be done with 25 cycles, the 15 cycles will certainly be used. As I have said before, it is solely a matter of dollars and cents.

Now, in regard to power distribution, I am much gratified to learn that the power required by the steam railroads entering Chicago is such an insignificant amount compared with that required for other purposes. For this very reason, there should be practically no interference in that case with the systems now in operation. The steam railroads certainly will require enough power when they electrify their terminals in and about Chicago, or any other large terminal, to build their own power houses and furnish their own power throughout. I do not believe it would be at all feasible for the company to draw, even to a very limited extent, from the lighting companies for power to operate their railways.

I agree with Mr. Stott that it is impossible for the various industrial plants to carry sufficient reserve capacity to take care of 25 per cent. or 20 per cent. of their normal load to provide for railway emergencies, particularly as the biggest railroad loads will come just as they do in street car service, at the hours of the day where the lighting load is heaviest and all the people want to travel at the same time. Steam railways must work out their own salvation. In electrifying their lines they must provide sufficient reserve capacity to take care of the entire system.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

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COMMUTATING-POLE DIRECT-CURRENT RAILWAY MOTORS

BY E. H. ANDERSON

General. In order to appreciate the development and reasons for the existence of a commutating-pole railway motor, it is well to discuss in some degree some other developments. In the beginning, railway-motor designers had many difficulties to contend with.

1. The question of gearing was possibly foremost, whether it should be single or double reduction or possibly gearless. All these were tried with more or less success. The pendulum swung back and forth from this point, but it has settled partly and is still settling. The small motor (automobile) is now more usually double reduction; however, in some cases, single reduction is used where weight is not of importance. The usual railway motor has settled down to single reduction. In the larger railway motor, where the work approaches that of a locomotive, it is often questionable whether single reduction or gearless should be used. When powers are small, as in the case of single-car units, the motor is naturally provided with single-reduction gearing. Then again, for large locomotives and high speeds, obviously the motor should be of gearless construction, this being especially true in the light of what may be done with gearless bipolar motors of direct-current design.

2. Possibly, insulation is next in order, various methods having been tried. The conductors have been covered with a variety of materials, but double or triple cotton-covered insulation has practically become standard. The slot insulation has been through various changes; for wire-wound machines it has settled down to a good varnished cambric with a protecting tape

of cotton, although an all-asbestos insulation of armature coils is promising.

Where bars are used as armature conductors, it is possible to insulate them entirely with mica. This type of insulation has been fully developed and may be considered as standard.

The field insulation has long been in a state of evolution, but is pretty well standardized on a basis of mica in metallic shells for the larger ribbon-wound field-coils, and varnished cambric for the smaller fields wound with wire. Here also an all-asbestos insulation is promising.

3. The present method of lubricating the bearings with oil has resulted from a process of elimination; many forms of grease-cups, oil-cups, wicks, etc., having been tried; in fact, the preferred lubrication at one time was grease.

With the advent of interurban trolley roads came greater speeds, giving rise to many more car-miles per day, and complaints arose of short life of bearings, injury to armatures, etc. The methods of lubrication underwent many changes, but are now well established as wool-waste and oil; no doubt a good solution of a difficult and important problem.

4. During this period of development, the armature was changed from a smooth to a slotted core, and much thought was given to the size of commutator, number of segments, turns per coil, etc., in the effort to produce successful operation of the commutator.

With all forms of copper brushes there was most destructive sparking and enormous local currents in coils short-circuited by the brush during commutation.

The carbon brush was tried and found to be the greatest improvement yet discovered in producing successful commutation. The greater contact resistance decreased the local currents to reasonable values, yet the energy lost by the greater contact resistance in the main circuit was small. The carbon brush thus opened up possibilities in design not before thought of.

The inductance of coils was reduced by placing two in one slot instead of one, thus saving insulation and reducing the diameter of the armature. Later came the three coils per slot armature, this being the standard for many motors to-day.

As motors had to be built to fill a restricted space, not only for large power and small diameters, but with good commutation at higher potentials, it gave rise to the four and five coils per slot armature. Many coils per slot necessarily increased the slot-width, and this in time called for a laminated-field pole structure in order to limit eddy-current losses. In the meantime the operator was demanding higher potentials, more work from the motors, and better commutation, and the commutation had not kept pace with other developments, in fact, was becoming more troublesome as compared with other difficulties, largely on account of higher operating potentials. Some means had thus to be adopted for radically improving commutation, and the following pages deal more particularly with this subject.

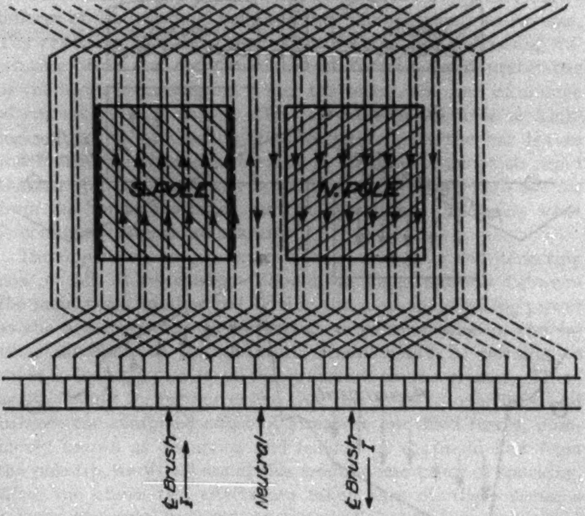


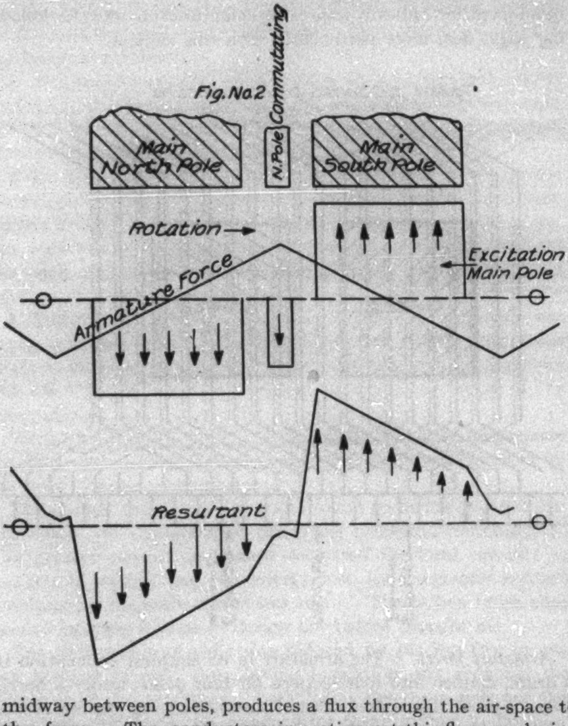
Fig. No. 1 D.C. Series Drum Armature
33 Slats 1 Coil per Slat

Armature forces. The armature in its simplest conception is a drum, divided into four sections for four poles; under a north pole is a broad distributed sheet of current running parallel to the shaft; under a south pole is also a broad distributed sheet of current, but in reverse direction.

This distributed armature current produces a magnetizing force which changes the distribution of the main flux in the pole-faces, as shown in Fig. 2. It will be seen that in the center of the pole there is no distributing effect, but in the center between poles there is the maximum magnetizing effect from the armature. This is where the conductors are commutated by the brush and the direction of the current reversed in passing from the zone of one pole to the zone of the next.

The magnetizing effect of the armature, being a maximum

Fig. No. 2


Commutating
N. Pole
Main North Pole
Main South Pole
Rotation →
Armature Force
Excitation Main Pole
Resultant

midway between poles, produces a flux through the air-space to the frame. The conductors in motion cut this flux, producing a voltage in the coil to be commutated.

The combined result of armature and field magnetizing effect is to cause a flux to leak from the pole-tip over into the armature just where the conductors are being commutated.

The two leakage fluxes are alike and add to produce voltage in the coil which is being commutated. Thus there is a potential between commutator-bars, and when these are short-circuited by the brush a local current is caused to flow in the coil under commutation. This local current adds to the line current already there. Any conductor carrying current has lines of force interlinked about itself caused by the current in the conductor. The conductors, imbedded in and surrounded on three sides by iron, have a good opportunity of surrounding themselves with a lot of leakage flux. The interlinkage of leakage flux is similar to the inertia in mechanics.

The combined current (line and local) has still greater interlinkage of leakage lines and becomes more difficult to reverse. The reversing has been done heretofore by the increasing resistance of contact between the brush and the commutator-bar as the latter is passing out under the brush, the rate of change of current ever increasing. This causes the reactance or kicking voltage to become higher and higher. As the bar leaves the brush, the change in current in the coil becomes so rapid that an appreciable voltage is induced and arcs through the air from the bar to the brush, or vice versa, thus producing what is commonly known as sparking.

The object is, then, to remove the sparking by counteracting one, or all, of its causes. Should we place midway between the main poles another coil, having the same magnetizing power as the armature, but so connected as to magnetize in the reverse direction to the armature, there would be nothing to cause a leakage flux from the armature to the frame. Then, again, should we further excite this coil so as to overcome and balance the combined effect of armature and field forces, commonly known as distortion and leakage of the main flux from the pole-tip, we would annul this troublesome cause of sparking. After the above two effects are taken care of, there remains a force necessary to produce a potential sufficient to reverse the current in the armature coil.

In order to produce this potential there must be such a density of flux as will generate this required voltage by the conductors cutting the flux in revolving. The width of such magnetic density should be sufficient to embrace the conductors commutated by the brush when running in either direction of rotation.

The commutating voltage produced by the flux of the commutating pole is the accelerating force required to change the direction of current in the armature coils one by one as they come under the brush. It must be sufficient to accomplish this in the time that the coil, being connected to two adjacent commutator-bars, is under the brush. When the commutator-bar leaves the brush, the current is already reversed, flowing in proper direction, and is of the proper amount, so there is no tendency to spark. Commutation may then be said to be perfect.

As stated before, an armature coil imbedded in iron is surrounded by a leakage flux, which is caused by the current in the coil, and may be said to have magnetic inertia or momentum. This is similar in mechanics to a revolving shaft bearing a mounted flywheel. The voltage induced in the coil by the flux from the commutating pole may be likened to a constant counter torque; this counter torque serving to slow down the revolutions, stop, and cause an increase in speed in the opposite direction.

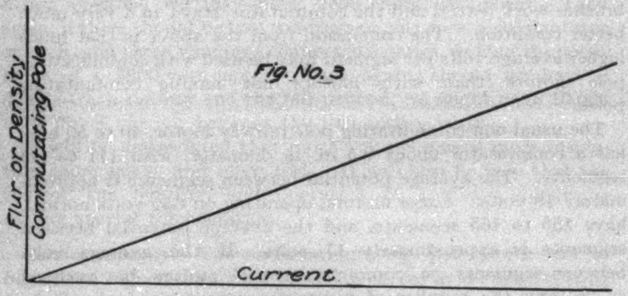
It is evident that there may be a particular armature current, speed of motor, and flux from commutating pole wherein the above described conditions will obtain. It will also be appreciated that the voltage induced by the commutating-pole flux will vary directly as the speed; furthermore, the time that the coil is under the brush is shorter as the speed is higher, and vice versa; also that the time required to reverse a current is inversely as the voltage. The conclusion is that the action is entirely automatic throughout the entire range of speed with the particular condition of current and commutating-pole density.

The next question is: can the action be automatic for varying current as well as speed? The commutating pole may be excited by the main current of the motor, being connected permanently in series with the armature. The commutating-pole flux will then vary almost directly as the current, which is the desired result. When the current is half, the commutating-pole flux is half, and the commutating voltage corresponding thereto. Thus the action is entirely automatic for variation in current or speed, or both.

Fig. 3 shows that the relation between commutating-pole density and current should be a straight line, rising and falling directly with the current.

It is well understood that an absolutely straight line between current and density cannot be obtained when a more or less saturated iron circuit carries the flux, but it can be approached sufficiently close for all practical purposes by careful design and experience in these matters. In a series motor the density of the whole iron circuit increases as the load comes on, and there is an increasing stability in commutation which serves to offset, partly, if not entirely, the lack of commutating-pole density on a heavy load. The combined effect is to produce perfect commutation at all loads.

Since the commutation is automatically taken care of for variations in speed and current, it is possible to change the voltage impressed on the motor through quite a range without sparking. This is thoroughly borne out by motors of 50 to 250 h.p., recently constructed in this country.



The only limitations in raising the voltage are:

1. Armature speed and strength of binding wire.
2. Volts between bars.
3. Insulation.

This brings us naturally to the question: what effect will this commutating pole have on designs for voltages higher than are now general for railway service?

Railway-motor commutators before being connected to the armature winding are tested from bar to bar with 400 to 500 volts, alternating current, which means a maximum of 40% more, so that actual jumping of current from bar to bar on a clean commutator would not occur at less than 500 volts per segment. An ordinary commutator of 111 segments and four poles would, under these conditions, be good for 13,000 volts between brushes. The actual jumping of current across side micas of a clean commutator is not the limiting condition.

The limiting condition is the voltage per bar which will maintain an arc already established. The allowable voltage per segment is largely dependent upon the condition of the commutator. The condition of the commutator depends upon the deteriorating tendencies, such as sparking and other causes, like poor carbon brushes, hard side micas, etc.

If the sparking is eliminated, the etching of the commutator-bars is largely reduced. The carbon brushes are required to carry only the line current, instead of the line and a large amount of local current; therefore the brushes are not disintegrated so rapidly. The carbon brush has less mica to wear off, because the bars are not burned away. The result is that the carbon brushes work better, and the commutator stays in a very much better condition. The conclusion from the above is that much higher average volts per segment may be used with commutating-pole motors than with motors not having commutating poles.

The usual non-commutating pole railway motor, 40 to 50 h.p., has a commutator about 9.5 in. in diameter, with 111 to 125 segments. The average potential between segments is approximately 18 volts. Large motors, operating on 650 volts normal, have 155 to 165 segments, and the average potential between segments is approximately 17 volts. If the average volts between segments on commutating-pole motors be assumed as 24, and the number of commutator bars per inch of circumference as 5, we have the following possible voltages on various sizes of motors and commutator diameters.

Horse power	Diameter of commutator	Maximum volts motor
40	9	850
75	11	1040
100	13	1230
150	14.5	1370
200	16	1510
250	18	1700

The above may be said to apply only as far as tendencies are concerned. Not all these various voltages would be practical. It would be better, for various reasons, to adopt 1200 volts as the higher standard.

The propositions requiring higher potential than 600 volts, are usually 30- to 50-ton cars with speeds of 40 to 60 miles per hr. These call for a motor of 75 h.p. or larger, so the sizes naturally fall where 1200 volts can be made with reasonable cost.

The commutating-pole motor, on 600 volts, makes possible commutation and general operation in service many times better than that of the non-commutating pole motor. On 1200 volts, the commutation is decidely better than with a non-commutating pole type motor on 600 volts.

The 1200-volt motor requires proportionally more insulation than the present 600-volt motor. This extra insulation requires more diameter and more external dimension.

Theoretical possibilities of voltage. We have the possibility of 1200 volts per motor, the motor having four poles. Should the motor be bipolar and the speeds high enough to make the design possible, we may have 2500 volts per motor. Then again, if there should be two windings on one core, a commutator on each, and these windings connected in series, we have the possibility of a 5000-volt motor. Then again, should we have a double-track railway and the rail neutral, we might have 10,000 volts direct current between the two trolley wires.

It will be appreciated that more voltage means more insulation, more space, and more cost. It will also be seen that the control, car lighting, and operation of auxiliary apparatus require special consideration.

Service capacity. The non-commutating pole motor has inherently a higher iron density, which serves as a compensating feature, improving commutation. The commutator-pole compensates for armature reaction and takes care of troubles due to lack of compensating features; a lower iron density may therefore be utilized and lower iron losses obtained.

The absence of sparking makes the commutating losses very much less. The rating on the hourly basis may not be much greater than with the non-commutating pole motor. On account of core-loss and commutator loss being considerably less, and these prominent features in heating, the commutating-pole motor has naturally a higher continuous rating; it is not only capable of taking large fluctuations of voltage and current, but will have a greater all-day service capacity. This latter feature becomes more pronounced as the distance between stops is greater.

There are several ways of making use of higher direct-current potentials. The most prominent of these are the following:

1. *a.* City service, 600-volt trolley.
Maximum speed 25 to 30 miles per hr.
Stops and schedules incident to city service.

b. Interurban service, 1200-volt trolley.
Maximum speed 50 to 60 miles per hr.
Few stops and high schedules.

The motors would be wound and insulated for 1200 volts.

Two motors would be connected in multiple, and the two groups of a four-motor equipment handled in series and in parallel.

2. *a.* City service, 600-volt trolley.
Maximum speed 25 to 30 miles per hr.
Stops and schedules incident to city service.

b. Suburban service, 600-volt trolley,
Maximum speed of 30 to 60 miles per hr.
Stops and schedules incident to suburban business.

c. Interurban service, 1200-volt trolley,
Maximum speed 50 to 60 miles per hr.
Few stops and high schedule speed.

The motors would be wound for 600 volts with a relatively low armature speed and insulated for 1200 volts.

On a 600-volt trolley two motors are connected in multiple. and the two groups handled in series and parallel.

On a 1200-volt trolley, two motors are connected in series, and the two groups of four-motor equipment handled in series and parallel.

The armature speed and commutating features should be so designed that if one wheel slips and one motor has 1200 volts or so across its terminal, its armature speed will be reasonable and the commutation good.

Interurban cars with four axles and four motors usually accelerate at 1 to 1.5 miles per hr. per sec.; this requires about 100 to 150 lb. per ton, which is 5 to 7.5% coefficient of traction. These are low coefficient values for interurban roads and are seldom met with; however, should slipping occur, the motor design should be such that no damage to equipment will result. In the city a dirty street may give a low condition of traction, but under these conditions, the motors may be used in multiple or operated as any four-motor equipment is now operated.

ADVANTAGES OF COMMUTATING-POLE RAILWAY MOTORS AS COMPARED WITH NON-COMMUTATING POLE TYPE

1. Sparkless commutation even on heavy overloads.

2. Flashing at commutator largely reduced and probably eliminated.

3. Less wear on commutator.

4. Cleaner and safer motor because of reduced carbon and copper dust from brushes and commutator.

5. Marked reduction in heating of commutator.

6. Greater current density in brushes.

7. Increased life of brushes.

8. Increased efficiency and free running capacity because of lower core and commutator losses.

9. Possibility of successfully using higher voltages.

10. Greater facility in design of large motors, especially as regards commutation.

11. Possibility of increasing service capacity of motors by blowing.

DISCUSSION ON "COMMUTATING-POLE DIRECT-CURRENT RAILWAY MOTORS", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

Gano Dunn: I see a tendency to hail the commutating-pole motor as the direct-current motor of the future. I heartily appreciate Mr. Anderson's paper, and the facts it brings out with which I am in substantial agreement; but I think it illustrates that we are liable to fads, and that the great success that has attended the introduction of the commutating pole so far has led some of us to attach to it too much importance. I regard the commutating-pole motor as applicable to certain classes of machines or conditions of design, such as low voltage, very large size, very high speed. These are found in direct-current turbo-generators, variable-speed motors, such as are known as field-weakening motors, railway motors where the space is crowded—in short, all machines where the commutating limit of capacity is reached before the heating limit. There still remain other classes of machines where none of these conditions applies. We have not yet exhausted our ingenuity in designing motors, so perhaps we may soon be able to equal in weight, cost, and efficiency, the commutating-pole motors, and without their complication.

It should be borne in mind that the commutating pole adds considerable complication. One of the principal advantages of direct-current motors in the past has been their simplicity, and simplicity is of first importance in electrical design.

It may be said that in a four-pole motor we need add only two commutating poles, and we may modify in one way or another the general type of the commutating-pole motor to make it more simple; but, when all has been said and done, we have a motor that has several more poles and considerable additional complication in its windings and connections.

J. C. Lincoln: Have these 1200-volt motors ever been used in practice?

E. H. Anderson: I do not know that there are any 1200-volt motors in this country in railway service. There are some contracts, however, which have been taken, and motors are building for 1200 volts. These motors have been tested on testing stands as high as 1800 volts for commutation.

W. N. Smith: Does the commutator require any more room, any more air-space around it, than with the older type of motor in order to prevent flashing-over to the frame in actual service.

E. H. Anderson: On the 600-volt motor there is usually about 1.25 in. flashing distance, and on some motors as low as 0.5 in. Dirt, copper, and carbon dust affect the flashing distance very materially. If we have a commutator which runs very much cleaner, does not have the copper and carbon dust, we do not need as much flashing distance. However, in order to improve in that direction, 1⅜ or 1½ in. creeping distances are allowed on 600-volt motors and 2 to 2½ in. on 1200 volts. The commutator does not need to be as long on 1200 volts as on 600 volts, because of less current to be carried.

A report presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y. June 27, 1907.

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PROPOSED CODE OF ETHICS.
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
COMMITTEE ON CODE OF ETHICS.

AMPERE, N. J., May 17, 1907.

To the President and Board of Directors of the American Institute of Electrical Engineers.

Gentlemen: Your committee, appointed at the annual convention at Milwaukee in June, 1906, to consider the advisability of preparing a code of engineering ethics, and, if thought best, to prepare such a code, has to report as follows:

While we do not consider it practicable at this time to formulate a code of ethics covering explicitly all the conditions which the electrical engineer may meet in his work, we do consider it both practicable and desirable to record some of the general principles of professional conduct that should be a guide for the electrical engineer, leaving it to him to make specific application to the cases which he may meet. We therefore submit and recommend the following, to be printed and distributed to the membership, with a view to its discussion and adoption at the approaching Annual Convention in June, 1907.

Respectfully submitted,
CHARLES P. STEINMETZ,
HAROLD W. BUCK,
SCHUYLER SKAATS WHEELER.
Chairman.

PRINCIPLES OF PROFESSIONAL CONDUCT FOR THE GUIDANCE OF THE ELECTRICAL ENGINEER.

A. General Principles.

B. Relations of the electrical engineer to his employer, customer, or client.

C. Relations of the electrical engineer to the ownership of the records of his work.

D. Relations of the electrical engineer to the public.

E. Relations of the electrical engineer to the engineering fraternity.

F. Relations of the electrical engineer to the standards of his profession.

A. GENERAL PRINCIPLES.

1. In both his professional and his business relations the electrical engineer should follow strictly the same ethical principles that are recognized in the social relations of every-day life. He should consider himself personally responsible for the character of the enterprises and the persons with which he is associated professionally.

2. Before entering into professional relations, it is therefore the duty of the electrical engineer to satisfy himself that the enterprises with which he connects himself are of a legitimate character. If, after becoming associated he finds them to be of a questionable nature he should sever his connection as soon as possible. It should not be considered an excuse that his connection extends only to legitimate engineering work.

3. An electrical engineer permitting the use of his name in any enterprise or exploitation becomes morally responsible for the character of the latter. He should therefore not allow the use of his name in connection with anything upon which he is not qualified by training and experience to exercise competent judgment.

4. The electrical engineer should take care that credit for engineering work is attributed to those who, as far as his knowledge of the matter goes, are the real authors of such work.

5. The electrical engineer should incline toward and not away from standards of all kinds, since standardization is peculiarly essential to the general progress of the profession. This applies to construction, measurement and expression, or nomenclature as well as to conduct, or ethics. Even the tendency to give individuality by providing special construction may sometimes be avoided with advantage.

B. RELATIONS OF THE ELECTRICAL ENGINEER TO HIS EMPLOYER, CUSTOMER, OR CLIENT.

7. The electrical engineer should consider the protection of his client's interests as his first obligation, and therefore should avoid every act that would be contrary to this duty; if any other consideration such as professional obligations or restrictions interfere with his so acting, in accordance with the expectation of his client, he should inform him of the situation.

8. He can honorably accept compensation, financially or otherwise, from one side or party only, interested in the same matter. The electrical engineer, whether consulting, designing, or operating, may therefore not accept commissions, either directly or indirectly, from other parties dealing with his principals.

9. Electrical engineers in a position to decide on the use of inventions, apparatus, etc., should not be financially interested in their use, as by receiving a royalty, etc., unless the matter is clearly understood by the client.

10. Electrical engineers should not accept employment while financially interested in a rival concern except upon the express permission of both parties. An electrical engineer may be employed by more than one party, as in the case of a consulting engineer, when the interests of the parties do not conflict and it is understood, as is usual in such cases, that he is not expected to devote his entire time to the work of one party

but is free to enter into other engagements. A consulting engineer permanently retained by a party should notify other prospective employers of this affiliation before entering into relations with them. A consulting engineer when not exclusively retained by one side may advise rival concerns, with the full knowledge of all of them and upon taking care that the interests of the parties do not conflict in the particular matter handled.

11. Operating engineers should consider themselves responsible for defects in apparatus or dangerous conditions of operation, should bring the same to the attention of their employers and urge remedial action. If the causes of the danger are not removed they should withdraw.

12. An electrical engineer should in general be considered directly responsible to his employer or client for the successful fulfilment of the work upon which he has been engaged and for its satisfactory performance as a whole. It should therefore be clearly understood at the outset just what the extent or the limitations of responsibility of the engineer are to be. Whether he has been employed merely as designer or whether he is retained to design and to superintend construction; whether to design only the chief features or to pass as well upon all details of the apparatus that is to be installed. Attention should be directed to the fact that defects in the manufacture of material or apparatus is a matter distinct from the matters of design or installation. An engineer should not be held responsible for the unsatisfactory performance of a plant resulting from defective apparatus furnished, unless he has undertaken to include this subject.

C. RELATIONS OF THE ELECTRICAL ENGINEER TO THE OWNERSHIP OF THE RECORDS OF HIS WORK:

15. The following general principles should be recognized:

If in executing his work, the electrical engineer uses data or information which are not common and public property, but which he receives, directly or indirectly from his employer, or if the problem solved by the engineer is met in the pursuit of his work for his employer, and is not of such character that his attention would have been directed to it regardless of his relations to his employer, the products of his work, in the form of inventions, plans, designs, etc., are not his private property, but the property of his employer, though the engineer may be entitled to special remuneration for such inventions, etc.

16. If in the execution of the work the engineer uses only his own knowledge or data or information which are public property by prior publication, etc., and receives no engineering data from his employer or customer, except performance specifications, the results of the work, such as inventions, plans, designs, etc., are the private property of the engineer, and his employer or customer is entitled to their use only in the specified case.

17. All the work done by the engineer in the form of inventions, plans, designs, etc., which are outside of the field of engineering for which his employer has retained him, are the engineer's private property.

18. When an engineer or manufacturer builds apparatus from engineering designs supplied to him by his customer, the designs remain the property of the customer and should not be duplicated for other cus-

tomers without express permission. When the engineer or manufacturer and his customer are jointly to work out designs and plans or develop inventions, a clear understanding should be arrived at before the beginning of the work regarding the proportionate rights of ownership in any inventions, designs, etc., that may result, since in such case both parties should be considered to have rights therein.

19. Any engineering data or information which an electrical engineer obtains, directly or indirectly, from his employer or customer, or which he creates as a result of such information, must be considered by the engineer as confidential; and while the engineer is justified in using such data or experience in his own practice as going towards his education, the publication thereof without express permission is improper, as is also its use in producing for other parties, work that is characteristic of the original customer or employer.

20. Designs, data, records and notes made during his engagement by an engineer employed under permanent engagement, and referring to his work, are his employer's property. The same matter in the case of a consulting electrical engineer are the property of the consulting engineer.

21. A customer, in buying apparatus, does not acquire any right in its design beyond the use in the apparatus purchased. A customer of a consulting engineer does not acquire any right to the plans made by the consulting engineer except for the specific case for which the apparatus was built or the plans made.

D. RELATIONS OF THE ELECTRICAL ENGINEER TO THE GENERAL PUBLIC.

22. The electrical engineer should endeavor to assist the public to a fair and correct general understanding of engineering matters, spread the general knowledge of electrical engineering, and discourage wrong or exaggerated statements on engineering subjects published in the press or otherwise, especially if these statements are made for the purpose of, or may lead to inducing the public to participate in unworthy schemes.

23. Controversies on engineering questions, however, should never be carried on in the public press, but should be confined to the technical press and the engineering societies.

24. First publication of inventions or other engineering advances should not be made through the public press but rather through the technical press and the engineering societies.

25. The publications which an electrical engineer is justified in making through the public press should therefore be of a historical, educational, instructive or similar character and should not relate to controversies between engineers or on engineering questions, to new inventions, etc., nor contain technical criticisms of fellow engineers, and it should be considered unprofessional to give opinions without being fully informed on all the facts relating to the question, and on the purpose for which the opinion is asked, with a full statement of the conditions under which the opinion applies.

26. In giving expert testimony before judicial bodies, the electrical engineer should confine himself to brief and clear statements on engineering or historical facts. He should not give personal opinions without so expressly stating, and should avoid pleading on one side or the other.

E. RELATIONS OF THE ELECTRICAL ENGINEER TO THE ENGINEERING FRATERNITY.

30. The electrical engineer should take interest in and show due regard for the electrical engineering societies and the technical press.

31. He should assist his fellow engineers by exchange of general information, experience, instruction, etc.

32. He should not take a position left by another electrical engineer without satisfying himself that the former has left voluntarily, or for proper reasons.

33. Where engineering work is in charge of an electrical engineer, no other electrical engineer should undertake the work except on request of or in coöperation with the electrical engineer who had charge of the work before, unless the latter's connection with it has already terminated.

34. An electrical engineer in responsible charge of work should not permit other engineers or non-technical persons to over-rule his electrical engineering decisions. If this is done and persisted in, he should as soon as is practicable withdraw.

35. In engineering work in charge of a board of engineers, the respective limitations of the authority of each should be decided at the outset, and each electrical engineer should give full and complete information on his part to the other engineers and insist on this being reciprocated.

F. RELATIONS OF THE ELECTRICAL ENGINEER TO THE STANDARDS OF HIS PROFESSION.

40. The title " electrician " should be applied to those having practical training sufficient to enable them to carry on intelligently certain classes of electrical work, such as the installation of electric lights, signaling systems, and the operation of small electric plants.

41. The title " electrical engineer " should be applied only to graduates from the electrical engineering schools of universities of recognized standing, and such men as possess an equivalent knowledge of electrical engineering.

42. The title " consulting electrical engineer " should be applied only to those electrical engineers who possess such knowledge and experience in electrical engineering as would qualify them to full membership in the American Institute of Electrical Engineers.

Signed,
CHARLES P. STEINMETZ,
HAROLD W. BUCK,
SCHUYLER SKAATS WHEELER.
Chairman.

DISCUSSION ON "PROPOSED CODE OF ETHICS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

Schuyler S. Wheeler: The report I have to present represents the work during the last year of a special committee of three consisting of Charles P. Steinmetz, Harold W. Buck, and myself. The committee was appointed at the last annual convention to take up questions that were raised by the presidential address of last year on the subject of engineering honor. This address brought up the subject of ethics and the professional conduct of engineers. A committee was appointed to look into the matter and see if any kind of a code should be prepared.

I am happy to say that our committee has been most harmonious in all of its conclusions. We have not disagreed over a single feature in the entire report. Another matter that I want to mention is that we have no idea that the present report is right throughout. We look upon it as a mere starting point, and we think that it will be very useful to us all, because it will at least furnish us what engineers call a datum line; and taking this we can go on with it and make improvements, and constantly make our list of principles better as time goes on.

The report was presented to the Board of Directors and accepted and ordered to be printed and sent to all of the members of the Institute in order that they might examine it so as to pass upon it intelligently at this convention.

William McClellan: I think that all of us at times have found the need of some such code as this. Questions come to us of more or less importance concerning which we should like to know just how other men of our profession would think. I believe that if this proposed code is examined carefully, it will be found that we are not limited or constrained by minor details but are given broad principles which may be interpreted according to the facts of the particular case. No doubt some of us would write such a code differently in details and would, perhaps, desire to have certain changes. This, however, should not prevent it from receiving favorable consideration from every member of the Institute.

Henry G. Stott: I think that the committee has done very admirable work in bringing together for the first time a code of ethics for the American Institute of Electrical Engineers, but there are some individual rules with which I do not agree at all. Take, for example, No. 11, which reads as follows:

> 11. Operating engineers should consider themselves responsible for defects in apparatus or dangerous conditions of operation, should bring the same to the attention of their employers and urge remedial action. If the causes of the danger are not removed they should withdraw.

Now, that is purely academic. Is there in this room any operating engineer who would do a thing like that? I for one would not, because the conditions may be such that it is absolutely impossible for the employer with all the resources at his command to overcome these defects. The operating engineer would not be doing his duty if he should withdraw; his duty is to stand by the apparatus and his employer until such time as the defects can be remedied.

I also take exception to the following rule, No. 12, which states among other things that,

> 12. It should therefore be clearly understood at the outset just what the extent or the limitations of responsibility of the engineer are to be.

Personally, I would not have a man work for me who started out with such a conception of his duties. I would want a man who would agree to accept responsibilities beyond what I ask him to accept at first, and I think every employer would feel the same way. I would not want to have it understood that an engineer is responsible up to that particular bolt or this particular plate and not any further, and the next man who comes along is responsible for what follows. If there is something wrong, is it not our duty, as engineers, to report it?

I think the rules are altogether too specific, and I would like to see them recast so as to make them broader.

Rule 20, states that designs, data, records, and notes obtained by an engineer employed on salary, are his employers' property; while the same matter in the case of a consulting electrical engineer paid by fee or by commission, are the property of the consulting engineer. I do not see the fine point in that distinction.

Then, again, Rule 26 as follows:

> 26. In giving expert testimony before judicial bodies, the electrical engineer should confine himself to brief and clear statements on engineering or historical facts. He should not give personal opinions without so expressly stating, and should avoid pleading on one side or the other.

The man who is on the stand giving expert testimony does not get a chance to express himself. It is entirely up to the lawyers as to what the man says. He usually says "Yes" or "No", and he does not get a chance to express his opinion.

Rule 32 provides:

> 32. He should not take a position left by another electrical engineer without satisfying himself that the former has left it voluntarily, or for proper reasons.

That is a perfectly correct attitude, but it may be there would be such a condition as that a man has been ill, or has absented himself from duty for some reason or other, and he cannot be reached. Under these conditions should we say that the employer has not the right to ask some one else to take up his duties if the man has absented himself? I think not.

H. W. Buck: Mr. Stott thinks that some of the rules are too specific. It was with the full knowledge of the committee that some of the rules were made very specific, and it was the belief of the committee that by only making them so radical and specific could general criticism be brought forth, by attracting attention to the various questions at issue. The committee realizes that many changes will have to be made, but I personally feel that if it is the sentiment of the meeting to have such a code at all, the best way is to recommend its adoption as offered by the committee. If it is allowed to lapse and further criticism is called for by correspondence or vote, I think it will simply result in the gradual disintegration of the proposed code through excessive criticism.

Charles F. Scott: I think that we should accept the report and have it published to the membership, with the strong endorsement it has in the names of the committee; that our Board of Directors should be asked by this meeting to continue a committee of this kind for consideration of suggestions which may be made to the committee and that the committee be asked to present a redraft of the report.

At the beginning of the next session, on Friday morning, June 28, 1907, **President Sheldon** said: The Chair will entertain a motion to the effect that the report of the Code of Ethics Committee be referred to the Board of Directors for their consideration.

[The motion was made by Henry G. Stott, seconded by Lewis B. Stillwell, and adopted by the convention.*]

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* For revised Proposed Code of Ethics as considered by the Board of Directors and submitted to the membership for suggestions, see Appendix, page 1789.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

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THE ATTITUDE OF THE TECHNICAL SCHOOL TOWARD THE PROFESSION OF ELECTRICAL ENGINEERING.

BY HENRY H. NORRIS

Introductory. The technical school is primarily an educational institution. The purpose is not to teach trades of any order, nor is it directly to produce business or professional men. The technical school sustains a vital relation to the profession of electrical engineering, and it cannot succeed without an understanding of that relation. On the other hand, the profession cannot use technical graduates efficiently without a knowledge of the purpose underlying their training. That both school and profession are coming to understand their relation is made evident by many signs. Among these may be mentioned the development of graduate-apprentice courses by manufacturing and operating companies, the reduction of manual training and the increase of scientific training in the schools, the formation of employment committees by both companies and schools, and the cordial relations existing between practitioners and teachers. From the first the technical school has stood for the encouragement of useful studies with a scientific foundation. At first undoubtedly too much emphasis was laid upon the practical features of the curriculum, and the attempt was made to do in the laboratory what can only be done in the factory. This and other faults are being corrected by the study of industrial conditions, and the work of the school is being increasingly appreciated by the profession generally.

The purpose of the present paper is to examine the methods of instruction in technical schools in order to ascertain how the requirements are being met, and to note the progress made and the prospects for improvement. Instructors in engineering realize that they are engaged in a most important business, that of preparing men for practical usefulness. In any industrial undertaking men are more necessary than money or machines, therefore the technical school works upon the most important element in commercial success. In many ways such a school is like a manufacturing establishment. It secures its raw material from the preparatory schools in the form of boys with crude ideas of practical life, with little conception of the purpose of a technical education, and with a fair preparation in several lines of study. During four years it endeavors by means of separate and assembling processes to produce men who can " do things." Thus the finished product of the technical school forms a most important part of the raw material of manufacture, construction, operation, and commerce.

Resumé of 1903 *convention papers on education.* At the Niagara Falls Convention of the Institute held in 1903 a profitable session was devoted to the discussion of technical education. Messrs. White, Gherardi, Osborne, and Jackson presented papers dealing with various aspects of the subject. The consensus of opinion expressed in these papers is that the personality of the technical graduate is of more importance than any information which he may have acquired. Professor Jackson emphasized that the function of a technical school is to produce a capacity on the part of the students for becoming engineers. It is the duty of a college to learn how to do this, the inference being that the teaching of special subjects is a means rather than an end. Professor Jackson's synopsis of the ideal engineer states that he is one who is competent to conceive, organize, and direct extended industrial enterprises. Mr. White selected a number of elements of a young man's personality which are important in business, and he summarized the results of a successful education as: (*a*), the satisfaction which results from possession; (*b*), the ability to enjoy good society; (*c*), the practical use which may be made of the training; (*d*), the ability properly to know any subject; and (*e*), the higher rank which will be taken as a result of this training. The employer inquires as to the business judgment, the mental capacity, and other similar characteristics of an applicant for a position. Mr. Gherardi separated the natural ability of a student from his school training. He does not believe that the training of a telephone engineer should be especially different from that of other electrical engineers, the training of any engineer properly consisting of such studies as will convince him of the necessity of getting facts, teaching him the best method of doing so. Further, these studies should train in the interpretation of engineering data and in reasoning from them. Mr. Osborne dwelt particularly upon the function of shop work in a technical training and pointed out that the training, as then conducted, tended to emphasize the importance of business rather than manufacturing. He argued for a knowledge of accounting, contracts, and other matters of direct importance in engineering.

Magnetic analogy of technical training. The effect of a technical training on a student may be considered as analogous to that of a magnetomotive force upon a piece of steel The latter possesses the ability to be magnetized on account of the inherent magnetism of its molecules. Before being subjected to the influence of a directive magnetomotive force, these molecules are grouped in such a way that no external effect is produced. When brought into a magnetic field the molecular magnets tend to arrange themselves in the direction of the applied force. The steel then becomes a magnet ready for any one of a number of practical uses. The external magnetomotive force has put nothing into the steel, but has merely supplied the incentive necessary to render available its inherent qualities. In a similar manner the young men entering technical schools possess certain elements and qualities of personality. The young men differ even more than do various samples of steel. The studies and the personality of the teachers supply what is needed to bring out and develop the natural aptitude of the students, and they can do no more. The student gets little that is new from his college course, and if the attempt is made to impart more information to him than is necessary to stimulate him to his best endeavors, his training will be to that extent a failure. Excess training produces saturation in the mind as does excess magnetomotive force in magnetic material. Like most analogies this one cannot be pushed too far. It emphasizes the fact, however, that the efficient training will be the one which aims most carefully at the development of the students' intrinsic qualities.

Problems of technical instruction. The difficulties encountered in technical education are not met in the delivery of certain courses. They result from the attempt so to coördinate these courses as to develop accuracy, quickness of perception, common sense, and such qualities. Leading engineers who are employers of technical graduates place greater value upon the personal qualities of the young men than upon their mere ability to produce designs and superintend construction. They expect the schools to turn out men of character as well as attainments. To meet these demands successfully requires attention to the following items: (1), the attraction and retention of desirable students and the exclusion of those not qualified for technical work; (2), the selection of such studies as will stimulate and direct mental activity; (3), the conducting of all courses in such ways as will tend to bring out the desirable personal qualities in the students; and (4), the recommendation to the students of those lines of engineering practice for which they are best suited.

Not a little of the success of all schools depends upon the quality of men who enter and upon the requirement of severe and continuous application. The results of the training depend very largely upon the personality of the student before he enters the institution. They are affected also by influences not directly resulting from study; for example, athletics and social activities. The direct mental effect of the studies is, therefore, not the only result, and possibly not the most important result of the training.

TECHNICAL SCHOOLS.

Historical notes—general. Technical education in this country may be said to have begun with the founding of the United States Military Academy in 1802, although no technical courses, in the modern sense, were given there. After its reorganization in 1817, an excellent system of mathematical and scientific instruction was given, forming a basis for practical army work. The first technical school, Renssalær Polytechnic Institute, began instruction in 1825. A course in civil engineering was gradually established to meet the demand of that time. The object of this school was to teach the application of science to industry, especially to agriculture, domestic economy, the arts, and manufacture. It is evident that the desire of the founder was to elevate the practical arts by a study of the principles underlying them. In 1845 the United States Naval Academy was founded, and another institution was added to the short list of those in which scientific and mathematical instruction was given with a practical end in view. The far-reaching effect of this discipline was noticeable in the early development of electrical engineering by the number of Annapolis and West Point men who were attracted to it. This occurred when the technical courses in electrical engineering were in the formative period. The demand of the time was for soundly trained and practical men, and these soon learned enough of electrical applications to enable them to take leading positions. Among these may be mentioned F. J. Sprague, (Annapolis, 1878), Louis Duncan, (Annapolis, 1880), W. D. Weaver, (Annapolis, 1880), S. Dana Greene, (Annapolis, 1883), and O. T. Crosby, (West Point, 1882).

As the demand for scientific and practical instruction increased, schools were established in connection with universities and upon private foundations, but it was not until after the passage of the Morrill Act of 1862 that a great impetus was given to them. The object of this act was particularly to encourage scientific and technical instruction. The results have been far reaching. Previously established schools were strengthened and many new ones were established, each having for its object the training of young people in practical arts. These schools are accomplishing and have accomplished a great work because their instruction has a definite end in view, that of producing independent, useful, and intelligent citizens.

The practical development of the telephone, the generator, the motor, and the electric light between 1870 and 1880 created a demand for technical instruction in electricity. By this time there were at least twenty-five institutions giving practical and scientific work, some like the Worcester Polytechnic Institute giving especial prominence to shop work, others combining the practical and scientific. The best example of the latter class was the Massachusetts Institute of Technology. In 1871 the Stevens Institute of Technology was organized and at once took a leading place through the prominence given by it to experimental engineering. A third class of schools was more purely scientific, being affiliated with the older classical colleges such as Yale, Harvard, Dartmouth, and Union. All of these schools became interested in the applications of electricity and the beginnings of electrical engineering study were made about 1880. The technical instruction in electricity lagged only a few years behind the industrial beginnings.

Historical notes—Sibley College. Among the land-grant colleges one of the most radical and least trammelled by tradition was that of New York State. Founded in spite of the opposition of every college in the state except Columbia, Cornell University was always ready to undertake anything that appeared promising.

The mechanic arts formed an important part of the curriculum from the start in the fall of 1868. In 1870 the Honorable Hiram Sibley of Rochester, N. Y., provided means for erecting a suitable building for the department and for purchasing the necessary equipment. The first degree of bachelor of mechanical engineering was conferred in 1873. The work in mechanic arts was administered by the late Professor John L. Morris from the beginning until his retirement in 1904. When early in the seventies William A. Anthony, then professor of physics, began experimenting with the "dynamo", the arc-light, and other novelties he received encouragement from President Andrew D. White. Professor Anthony, assisted by Professor G. S. Moler, designed and built in 1875 a Gramme machine and instruments for experimenting with it. Still earlier he had a telegraph line about the campus; this was transformed into a telephone line as soon as the telephone appeared. An arc-light system with underground cable was also operated. All of these electrical applications impelled him to give instruction in physics with special reference to electricity. In the spring of 1883, while visiting the physical laboratory, President White was impressed with the interest in electrical matters manifested by the students. From his association with Ezra Cornell he was familiar with the development of the telegraph and he had also noted the work done with the electric motor in Germany. Among the experiences which he remembered with pleasure were the rides taken in 1879 upon the Siemens train at the Berlin Exposition of that year and upon the Lichterfelde road. He was also pleased with the Jablochkoff candle in Paris. While talking with Professor Anthony about the rapidly developing art, he suggested that there might be occasion for a new course of study, that of electrical engineering. Professor Anthony agreeing with this suggestion, immediately prepared a plan for a course and presented it to the trustees on March 22, 1883. The trustees referred the matter to the faculty and on March 26 authorized the announcement of a course in electrical engineering.* The announcement was made and several students were attracted by it. The register for the following year states:

> The rapid development of the application of electricity has created a demand for thoroughly trained engineers conversant with electrical

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* An electrical course had been begun during the previous year at the Massachusetts Institute, but President White had not heard of it, nor had he received any applications for electrical instruction.

science, especially by companies carrying on telegraphy, electrical lighting, electrical supply and transmission of power, electroplating or the manufacture of electrical machinery and apparatus. Recognizing this demand, at the beginning of the past academic year the trustees of Cornell University began to receive students desiring to fit themselves to enter this new and constantly extending field. While the general studies of the new course are mainly those of the departments of Civil Engineering and Mechanical Engineering, the special studies of the course embrace the theory of electricity, the construction and testing of telegraph lines, cables, and instruments, and of dynamo-machines, and the methods of electrical measurements, electrical lighting, and the electrical transmission of power.

The electrical course proved popular and developed rapidly. Upon the transfer of the late Robert H. Thurston from Stevens Institute to the directorship of Sibley College in 1885, the electrical course was transferred to Sibley College and became a division of the mechanical engineering course, as it is to-day. The change was based upon the necessity for a thorough foundation of mechanics in the study of electrical engineering. As the major part of the work was given in Sibley College it was natural that the students should come under the jurisdiction of that faculty. The test of time has amply demonstrated the wisdom of this arrangement.

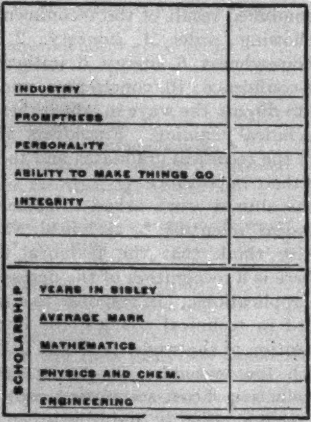
Present curriculum at Sibley College. The present curriculum of Sibley College is the result of a continuous attempt to give a practical education upon a scientific foundation. At first much attention was devoted to manual training, but this has given way to the principles of manufacturing. Experimental engineering has had an increasingly large place. The "backbone" of the course in mechanical engineering is mechanics, theoretical and applied. Analytical geometry and the calculus in the first year lead to the mechanics of engineering in the second. The physics and chemistry of the first and second years give a scientific basis for their practical applications. The descriptive geometry of the first year prepares the way for mechanical drawing. In the second year this takes the form of elementary machine design and kinematics, followed by the more advanced machine design in the third year. A limited amount of shop work is given in the first, second, and third years with accompanying lectures on shop administration and kindred topics. Engineering work begins in the third year with the principles and practical applications of steam and electrical machinery. Experimental work in the electrical and mechanical laboratories continues throughout the third and fourth years. During the first three years the instruction in mechanical and electrical engineering is identical, Considerable specialization is allowed during the fourth year, the student taking, as a division of general mechanical engineering, electrical, railway, marine or power engineering, machine design, or naval architecture.

Electrical engineering is taught as an application of mechanics, the only difference from other branches of mechanical engineering being in the source of the forces and the methods of transferring and transforming energy. The alternating current is studied from the start upon the ground that it gives a simple, general, and logical application of the laws of mechanics. The students appear to grasp the applications most readily in the following order: transmission lines, transformers, induction motors, alternators, synchronous motors, synchronous converters, continuous-current generators and motors, and special machines and devices. In connection with each of these topics the auxiliaries are discussed in their logical places; for example, with transmission lines; switches, fuses, and lightning protection.

The electrical instruction is three-sided; experimental, analytical, and graphical. In the laboratory numerous experiments are conducted upon various types of machines, and data (facts) are collected. In the class room the performance of the same machines is predicted from the physical laws underlying their operation. In the computing room the theory and the facts are brought together in graphical form and are thus compared and verified. No designing of electrical machinery forms part of the required course, as this is largely empirical, depending upon the judgment and trained instinct of the practical engineer. Instead, the student is taught to predetermine the characteristics of machines from the dimensions and arrangement of their electric and magnetic circuits, each machine being reduced to an equivalent electric circuit. The computing room is a useful adjunct in this work. While it is not possible to have all of the laboratory reports prepared and problems solved under instruction, a beginning is made, the reports being completed at home. The work of the fourth year is not wholly electrical, but a course in power engineering is taken by all. The mechanical laboratory also tends to prevent undue concentration upon the one subject. A course in political economy also draws attention to important phases of business and social activities.

In addition to the required courses, a considerable part of the senior year is available for elective work in engineering subjects. The electrical elective studies comprise electric railways, telephone engineering, electrical machinery design, and power generation and distribution. These are given in the second half of the senior year, after the major part of the routine work is complete Thesis work may be taken as an elective when a suitable subject presents itself for investigation.

The course described is essentially that given in all technical schools, although details and arrangement differ with environment. Sibley College is fortunate in being connected with a large university which undoubtedly tends to interest the technical students in matters outside their specialties and thus broadens their horizons. On the other hand, the university acknowledges the stimulus received from the technical school through the energy displayed and the practical nature of the studies.



	INDUSTRY	
	PROMPTNESS	
	PERSONALITY	
	ABILITY TO MAKE THINGS GO	
	INTEGRITY	
SCHOLARSHIP	YEARS IN SIBLEY	
	AVERAGE MARK	
	MATHEMATICS	
	PHYSICS AND CHEM.	
	ENGINEERING	

Results of technical education. It requires no further argument to prove that in importance personality precedes scholarship in the makeup of the technical graduate. Some years ago Professor Harris J. Ryan devised the foregoing form to be filled in when an estimate of a student's characteristics was requested.

This form is still in use by the Employment Committee and it is of great service in making recommendations. The words "excellent," "good," "fair" and "poor" are used in grading the students for the purpose. Proceeding upon the assumption that the personality is of prime importance, the writer, for the purposes of this paper, requested a large number of Sibley alumni of from four to twenty years' standing to state whether or not the training affected honesty, thoroughness, initiative, perseverance, accuracy, conciseness, energy, self-confidence, address, alertness, and loyalty. Practically all testified that these items are affected and as a rule favorably. Further the alumni were asked to arrange these elements in order of importance. The combined result of the recommendations placed them in the following order: 1, honesty; 2, perseverance; 3, accuracy; 4, thoroughness; 5, energy; 6, initiative; 7, address; 8, loyalty; 9, self-confidence; 10, conciseness; and 11, alertness. It is unnecessary to discuss the ways in which these elements are affected by a technical training. Employers are justified in expecting them in the technical graduates and the schools must and do recognize their importance.

Incidentally, the alumni were asked to state which part of their courses, classical, scientific, or technical, was most beneficial. The majority think that the technical studies benefit them most but there is a recognition of the necessity for a scientific basis for the applications. In response to a query as to improvements needed in technical courses, the impression seems to be that the attention of the students should be directed to the purposes to which the principles are to be applied. A few advocate the introduction of cost-accounting, contracts and allied subjects, which are undoubtedly desirable when time permits. A fourth question asked was, "In what particulars have you found your technical training useful?" This elicited many interesting opinions. *Practically none referred to any technical information which had been received in college.* Instead the opinion was that the greatest gain was the habit of scientifically and practically attacking and solving problems as they arise. General adaptability and the faculty of securing information when needed along any line were also mentioned as important.

After all, the best test of a training of any kind is the use made of it. To determine what the Sibley alumni are doing a canvass of the entire number was recently made. From partial returns the following table has been compiled.

TABLE OF PRESENT OCCUPATIONS OF ALUMNI OF SIBLEY COLLEGE.

(Includes over 80% of the alumni up to 1904)

Occupation.	Number.	Per cent.
1. Mechanical engineer	298	23.20
2. Electrical engineer	170	13.23
3. Designer or draftsman	140	10.90
4. President, vice-president, secretary, treasurer, or member of firm, manufacturing	127	9.88
5. Teacher	114	8.88
6. Sales engineer	107	8.33
7. Consulting engineer	43	3.35
8. Manager or superintendent, operating	41	3.19
9. Non-engineering occupations*	39	3.03
10. Manager or superintendent, manufacturing	32	2.48
11. Foreman	31	2.41
12. Manager or superintendent, constructing	25	1.94
13. Insurance engineer	19	1.48
14. Attorney	18	1.40
15. Army or navy officer	17	1.32
16. Editor or publisher	15	1.17
17. Assayer, geologist, or mining engineer	15	1.17
18. President, vice-president, secretary, treasurer, or partner, constructing	13	1.01
19. Patent examiner	8	0.62
20. President, vice-president, secretary, treasurer, or partner, operating	7	0.54
21. Civil engineer	4	0.31
22. Irrigating engineer	1	0.08
23. City engineer	1	0.08
Total	1285	100.00

Comments. The first three items may require some explanation. By the term " mechanical engineer " is meant those who are rated as such or who are doing general mechanical engineering work. Designers, draftsmen and those engaged in administrative work are classed separately. The same remark applies to electrical engineer. The word "designer" covers those engineers, however prominent, who are primarily engaged in preparing or superintending the preparation of drawings and designs. It is interesting to note the large number engaged in actual engineering work. There is, however, a great tendency on the part of young engineers to enter sales departments.

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*The non-engineering occupations are as follows: Bankers 4, car agent 1, chemist 1, dairy farmer 1, dentist 1, druggist 1, flour miller 1, healer 2, hotel manager 1, jeweler 1, librarian 1, mechanics 4, merchants 7, paper hanger 1, photographer 1, physician 1, postal clerk 1, real-estate agents 3, secretary department of public charities 1, stock broker 1, sugar planter 1, time-keeper 1, tobacco dealer 1, tobacco planter 1.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

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ON THE CONCENTRIC METHOD OF TEACHING ELECTRICAL ENGINEERING

BY V. KARAPETOFF

Introduction. The aims in teaching electrical engineering must be in accord with the demands of the electrical industry, and with the needs of the country, broadly understood. The details of electrotechnical pedagogics should properly be discussed among the teachers themselves, but the principles and the aims should be established through close coöperation with national technical bodies, such as the American Institute of Electrical Engineers.

The manufacturer of machinery learns from the user in how far his product has been successful; so the teachers of electrical engineering turn to the representatives of the electrical industry at large for advice and direction. The teacher of engineering wants to know what product is desired, and what faults are found in present technical graduates.

The concentric method of education outlined below is one which it is thought will supply the needs of industry better than the present method. *From theory to practice is the present motto*; *from practice to theory is the new principle proposed.*

SOME REMARKS ON THE PRESENT METHOD

The established educational custom is to begin the teaching of every technical subject with *theory*, gradually turning to *practice*, as based on theory. That this method is the only logical one has seemed to be almost self-evident, it being generally understood that practice cannot be taught without theory. But the question is, can theory be successfully taught without previous practice? Is teaching engineering merely the filling of a man's mind with detached facts, or does it mean developing his ability, to the end that he may think logically in his profession, getting correct results by correct processes? If the latter, the coöperation of the student must be secured at the very start and maintained throughout the course. The immature mind of eighteen years is entirely blank so far as the theory and practice of engineering are concerned. Can this coöperation be secured more easily by teaching him abstract auxiliary sciences, like mathematics, mechanics, and physics, as is now done, or by hurrying him into his profession at the very outset?

The writer's principal objection to the present method of teaching engineering is that student is burdened with abstract *auxiliary* sciences during the first two years of his college course, before he has had even a taste of his profession. The conscious coöperation of the student is not assured. Rather, he follows the prescribed courses blindly on the supposition that he is being properly cared for. It always reminds me of going to a dentist or to a barber, where we pay a specialist and passively submit to an unpleasant but inevitable operation.

It is perfectly evident to us that mathematics and mechanics, physics and chemistry, constitute necessary correlatives for engineering courses, just as history and economics are necessary for the study of the law. But this is not obvious to the beginner; he is all at sea in studying subjects without knowing their application. *All auxiliary subjects of study must follow the principal study and not precede it, as is the case with the present system.* I know this would mean to reverse entirely all the present plans of instruction, but what is right ought to be done at any cost.

No subject should be taught in which an interest can not be aroused. This means, do not begin with the elements, because they are not interesting; "*begin from the end.*" In teaching Latin do not give in the freshman year dry grammar and other dead stuff. Begin by reading the best examples of Roman literature in English translations. Then let the boys decide whether it is worth while for them to spend several years in studying the language in order to enjoy these same monuments of human genius in their original form. Is not a great mistake committed continually in making our young people study dead languages for years, only to find in the end that ninety-nine per cent.

of them cannot then read Latin and Greek authors well enough to enjoy them.

The same mistake is made in mechanic arts, by beginning the course with elementary operations, forging, filing, etc., which arouse very little interest. Let the freshman begin his work by making a simple but complete piece of apparatus, wherein all the essential operations enter in their simplest form; let him discover himself the necessity of all these operations, then begin to study them in detail. If a student cannot be interested in making a piece of machinery where he has to perform all shop operations, this student is not fitted for the engineering course, and should be advised to change his specialty. *But if he is interested, then his coöperation is assured* and it becomes an easy task to teach him the details of his profession.

A great problem before technical educators is the evil of early specialization. But teaching mathematics and physics is no remedy; a true broadening effect is exerted only by a study of actual life, of practical economic conditions. Explain to the freshman the significance that various branches of engineering possess for the welfare of the country; this will have a much more broadening effect than studying the equation of an ellipse or the properties of barium. This is exactly what the proposed concentric method has in view, as may be gathered by reference to the schedules in the appendix to this paper.

In colleges of applied science all courses of instruction should consist, in the freshman year, in explaining the practical side of the profession and the social standing and opportunities of men in them. The engineering colleges should demonstrate the operation and application of all kinds of machinery; the practical side of building bridges and constructing railroads, etc. The college of law should have popular lectures on the practical work of lawyers, judges, and other men engaged in preserving justice among men. The college of medicine should give practical demonstrations in different specialties of medical work, and so on. A freshman should be offered an opportunity to go to all these lectures and to see what specialty he likes best. Let him even lose (?) a year if he has not selected any profession; for this is much better than to study three years under the present system, and, after coming to his senior year, to the practical side of his profession, to find himself sadly mistaken in his expectations.

Let us begin from the end, then, let us exchange the freshman and the senior years; let us first give the student the fruits of knowledge, then, if he likes them, he will be interested to learn of their theories and foundations. Of course, freshmen cannot be taught engineering or law in the same way that these subjects are taught to juniors and seniors; but who would venture to say that these subjects could not be taught in a more popular and interesting manner than at present?

WHAT THE CONCENTRIC METHOD IS

The method of instruction for which the author stands may properly be called the "concentric method," and is represented graphically (Fig. 1) by a series of concentric circles; each zone comprises as far as possible the whole scope of a given specialty. The knowledge represented by different zones differs only in the degree of specialization.

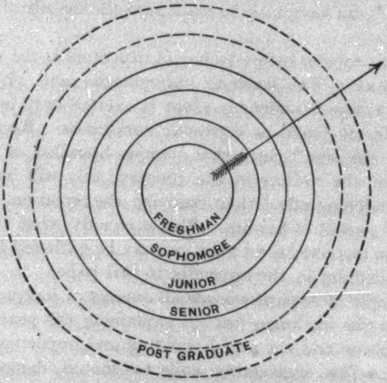

FIG. 1—Concentrically widening the student's mental horizon

During the freshman year (inner circle) the student is introduced to the whole scope of his profession, though in a very elementary, popular manner. The next year (second zone) he studies the same subjects from a somewhat more special point of view. The third zone represents the same subjects still more advanced, etc. For example, in applying this method to the study of history, the first zone would represent a broad sketch of the destinies of different nations; the next zone would be a more detailed treatment of the most important historical periods; the third zone might include a critical study of original sources and actual remains: and the fourth, the philosophy of history. Or, in studying the steam engine, the first circle corresponds to a purely descriptive sketch of the operation—handling and troubles—the second a more detailed study of the parts and an experimental investigation of the accompanying phenomena; the third year would comprise the theory of these phenomena from the standpoint of thermodynamics, mechanics, strength of materials, etc. The outer zone would represent design and special investigations. The dotted circles on the

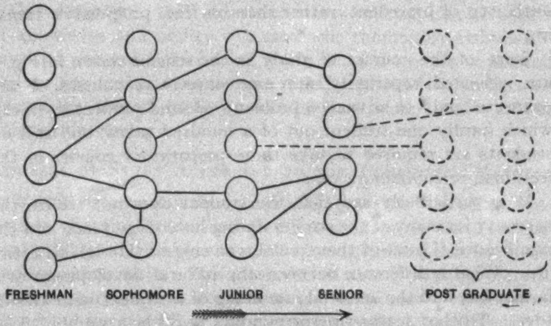

FIG. 2—Lack of system in the present way of instruction (subject method)

diagram represent advanced post-graduate work and symbolize infinity of knowledge.

In contradistinction to this system, the method now in vogue, or the "subject method," is represented in Fig. 2. Here the student begins his freshman year by studying several subjects of an abstract character, subjects having no relation whatever to each other. They are in part auxiliaries for consecutive studies, in part are supposed to develop logical thinking and imagination. The subjects introduced the second year are based partly on the studies of the previous year, partly represent new departure; but again their relation to the principal subject of study is not sufficiently evident to the student, so that he blindly and reluctantly follows the program, instead of coöperating actively.

In the third year, the professional studies begin, based on the sciences absorbed during the first two years. But these studies are again of too academic a character, too abstract, since the whole underlying idea with the present system is that practical applications must follow the general theory. Thus only in his senior year does the student come to the practical side of his profession. This method is probably the easiest for the teachers, because they also were educated in this way; but unfortunately it contradicts the very nature of man, and stands in contradiction to the educational aims of our times. The method has a distinct stamp of old scholastic culture based on the authority of precedent, rather than on free progressive thinking.

Some of the courses of study in the scheme shown in Fig. 2 are indicated separately from any consecutive courses, or are connected only to advanced problems (dotted connecting lines), which hardly one student out of a hundred takes; and still all students are required to take these preparatory courses in the freshman or sophomore year.

It is particularly sad that the student does not realize the necessity for many of the studies during his college years, and the significance of some of them remains an enigma through his entire life. What a difference between the natural development of a farmer boy and the artificial cramming of a student with knowledge, The boy learns the surrounding world in a purely "concentric" manner; the student is taught according to the "subject method." The farmer boy begins at once with botany, zoology, law, mechanic arts, and enlarges his knowledge gradually as he feels the need for it; and he is more and more interested in the results of such knowledge or experience. The student begins with the most abstract knowledge, or fragmentary practice, which he cannot connect with his life. The farmer boy lives to-day; constantly he applies his knowledge or at least realizes its use; the student lives with the expectation that some day he will understand the use of the dry stuff he is forced to imbibe, or perhaps be allowed to forget it. How can any great success be expected under such circumstances?

We are beginning to understand that true preparation for an activity consists not in mechanical ability to perform simple operations, or in knowing abstract elements. The mind of the man must be made receptive by impressing him with the important or interesting side of his subject; this can be done only by showing him the result before he begins an extensive study.

It seems that with our present system we are preparing students, not for ordinary commercial work which ninety-nine per cent. of them take up, but for special research work, which hardly one per cent. ever follow. In doing so we are involuntarily tempted to make of the students what we ourselves to some extent are—men pursuing more or less original research rather than regular commercial work. *Let us remember that we are supposed to prepare, not future professors, but men for industrial work, and that our first aim should be to comply with the needs of the industry.*

Our democratic and industrial times call for infinite stages of knowledge and ability. A man who thoroughly assimilates, say, two concentric circles of study is of more use to himself and to the nation than a man filled with useless undigested knowledge, though in his pocket he have a diploma from our greatest university.

COURSES OF STUDY ACCORDING TO THE CONCENTRIC METHOD.

We will suppose now that the reader agrees with the above contention, that the best method of education is that in which the student gets first a bird's-eye view of his profession, and then improves and specializes in it. This method is in accord with our nature, permits everybody to go just as far as he can or wishes; an element of interest is introduced into the study; a hastily selected vocation may be easily changed, etc. The question arises: is this method practicable? Can courses of study be arranged according to the above principles? As an answer the writer gives below an outline of a complete four- or five-year course of study of electrical engineering according to the concentric method. It seems to him that any other subject could be arranged just as well, since electrical engineering is no exception.

The present course in mechanical and electrical engineering may be called "from abstract to concrete"; that is to say, the course begins with mathematics, mechanics, and physics, then passes through an intermediate stage of machine elements, strength of materials, drawing, etc., and finally advances to the electrical and mechanical engineering proper. The courses in engineering proper are also arranged somewhat from abstract to concrete, so that general theory precedes the experimental and empirical side of study. The proposed courses, arranged according to the concentric method, follow the opposite way, "from concrete to abstract", the idea of each year being characterized as follows:

Freshman. Introduction into electrical engineering (bird's-eye view).
Sophomore. Experimental electrical engineering.
Junior. Elementary theory of electrical engineering.
Senior. Advanced theory of electrical engineering.

Freshman year. The fundamental course of this year should be "Electricity in modern life," or "Cyclopedia of electrical engineering." This course should comprise the following divisions:

1. A popular outline of applying electricity to lighting, railways, telephones, signaling, metallurgy, chemistry, medicine, etc.; popular experiments must make it perfectly plain and intelligible to everyone, so that students of all departments could easily and with interest follow the course. This is in accordance with the idea that during the freshman year the student is not supposed to have definitely selected his specialty.
2. Talks on the general character of engineering work, on opportunities and social standing of engineers, on necessary qualifications for different kinds of work, etc.
3. A historical sketch of the development of the electrical industry, and its present state in this country and abroad.
4. Explanation of the concentric method pursued during the four years, and an outline of the consequent work during this course. This is desirable in order to insure the conscious cooperation of the student in his future work.

A similar course should be given in mechanical and possibly in civil engineering; these three courses constituting the most important part of the freshman year. If the student feels that he cannot yet decide to become an engineer, or what kind of engineer he wants to become, let him spend the rest of his time in going to similar popular lectures in other departments of the university. But if he has already decided that he is going to become an electrical engineer, he may be given some work in the shops and the laboratory. This should be not the so-called *elementary* work, consisting of filing, or measuring specific heat and resistances, but *practical* work, consisting of assembling and dismantling of apparatus, handling machinery, electric wiring and connections, etc., so that he may feel that he is already started in his profession. This consciousness would give him pride and satisfaction, and arouse his interest for further studies. *This purely psychological element of technical education is almost entirely lost sight of with the present system.*

Freshmen should not have more than, say, 12 hours a week of engineering work, and should be induced to take a few courses of a general character in other departments, rather than allowed to specialize in one kind of work. Experience may show that there will be some demand for mathematics and physics on the part of the students themselves; should such be the case, the corresponding courses could be easily provided.

The writer wishes to emphasize the fact that he by no means belongs to that class of " practical men ' who sneer at any theory, and do not consider physics and mathematics as a part of engineering education. He himself is very fond of these sciences and preferably spends his hours of leisure in studying them. Yet he firmly believes that for engineering purposes physics and mathematics are of an auxiliary character and should be given the students only as such Moreover, these sciences should be taught so that the student may clearly see their importance and necessity in his profession. Later on, during his senior year, or after graduation, a student who feels an academic interest in these sciences may specialize in them; but *his first duty during the freshman and sophomore years is to study engineering, and not physics and mathematics.*

Sophomore year. Electrical engineering should be treated during this year purely experimentally, keeping in mind that while the underlying phenomena are unchangeable, all our theories and explanations are rather poor excuses for our absolute ignorance of the true nature of electricity and magnetism. Thus the electrical engineering courses during this year should comprise construction and operation of electric machinery, lamps, street-car equipments, telegraph and telephone apparatus, etc., going more into detail than was possible during the freshman year, where it was necessary to establish in the first place the very possibility and scope of applications of electricity.

Hand in hand with this course should go electrical laboratory work, not in the sense usually applied now, that is to say for the purpose of getting some numerical results, but simply for the purpose of handling all kinds of electrical apparatus. This should impress the student that the apparatus studied is something real and substantial and not mere fiction or schemes drawn on the blackboard. Lectures in mechanical engineering and mechanical laboratory should be of about the same character; it is not at all necessary or important for an electrical engineer to know much about thermodynamic calculations, but he must be sure that, if necessary, he can take care of boilers, steam, and gas engines, pumps, etc.

Shop-work must again consist in making pieces of simple apparatus comprising as many different operations as possible; no "single" operations should be allowed at this stage, because it would immediately lower the interest in the work. As a novel feature, some electrical work might be introduced, such as making blade-switches, simple measuring instruments, and spark-coils. In building such apparatus the student will meet with most of the shop operations and will get the necessary preparation for taking up regular shop theory and practice during the next year.

The study of mathematics, physics, and mechanics can be profitably begun during the sophomore year, provided they be taught *by an engineer and from the standpoint of engineering applications*, rather than abstract theory. Moreover, in order to link this course with engineering and with the mathematical knowledge required at the entrance examinations, this course should begin with applications of elementary mathematics to engineering problems, the students being tactfully brought to seemingly elementary problems, where analytics and the calculus become necessary. In this way the mind of the student is brought to an understanding of the practical importance of considering infinitesimal parts of time, length, volume, etc.; and thus partly by intuition, partly by application, he is introduced to analytics and the calculus.

Drawing, both freehand and mechanical, must be taught, not as an art by itself (unless the student desires it), but simply as a matter of necessity in shop work and in laboratory reports; the same holds true of descriptive geometry. The laboratory work, the shop practice, and possibly some class exercises should be so arranged that the students may *naturally* come to use drawings, both those given them and those made by themselves. Thus they will gradually recognize the necessity of plan, elevation, cross-section, perspective, schematic representation, and other technicalities. In the opinion of the writer, drawing should be taught in engineering colleges just as writing is taught in good primary schools. There the child is skillfully brought to an understanding of the advantages of putting down its needs on paper, and of reading the ideas of other people.

Junior year. Now comes the third year. With the present system the student begins dimly to realize at this time the very first principles of his specialty. With the system here proposed the student begins his third year with a more or less definite idea of the whole scope of his specialty; he knows that he is going to study the details of the work of the previous years and that he was lacking last year such auxiliary sciences as mathematics, physics, and chemistry. Now he is prepared to appreciate their significance; even more, he is already absolutely sure of their necessity, and is willing to accept the teacher's word even though he does not see its immediate application. Thus the work of the junior year should include a study of mathematics, physics, mechanics, chemistry (auxiliary sciences) with particular reference to electrical and mechanical engineering; at the same time a deeper insight into the specialty is made possible, assisted by these sciences.

The study of engineering may now be taken up with numerical relations. It is not necessary to go at once into higher mathematics, but merely to establish such relations as may be deduced from experiments, and which may immediately be applied to the solution of practical problems. With the training of the two previous years, the educator need not fear to go into details, since the student is already able to understand the significance and the place of a particular problem in the general field of electrical engineering.

To expect a student to investigate numerically this or that property of an electric machine the first time he sees the machine in the laboratory, as is the case under the present system, does not seem very rational. The purely qualitative and constructive side is of much more importance than any precise measurements. But if he has already had electric machines before him for two years, as with the proposed concentric method, he certainly can be made interested in numerical relations during the third year; and these measurements will be of a much better quality because he already knows how to handle machinery, apparatus, and measuring instruments.

Shop-work at this stage should consist in a systematic study of different operations: machining, forging, making castings, wood-work, etc. The work of the two previous years has shown the student *the necessity* of all these operations, and the relative positions they occupy in the processes of manufacturing. Now he will find interest in going into the details of each operation. Of course, it should be understood that the final purpose is to know how to direct and specify shop-work, rather than merely to acquire manual skill. This work should be supplemented by lectures on the subject, which would unify the methods taught in the shops, extend them beyond the possibilities of college shops, and also treat of cost of production and of methods of accounting.

Senior year. With the present system a senior hears for the first time the most elementary things in practical engineering; at the same time he knows (or is supposed to know) all about many theoretical laws and abstract relations studied during his junior and sophomore years. With the proposed concentric system he would already know a good deal about construction and operation of machinery from his three previous college years, but would lack the theoretical knowledge necessary for independent original work and design. The senior year is supposed to give him this, on the basis of the practical knowledge acquired during the previous years. Let us begin from the end.

The senior year should be devoted mostly to the theory of electrical and magnetic phenomena on the firm basis of previously established experimental relations. The educator may now boldly go into the very depths of mathematical analyses, for a senior understands their significance, whereas our present freshmen and sophomores merely get a chronic mental indigestion from the sight of mathematical formulas—an indigestion that often lasts a lifetime. It is a truism that the average technical graduate instinctively dodges differential coefficients and the symbol of integration.

In addition to pure theory, special elective courses should be given, such as electrical design, electric railways, telephony, etc. Such electives are given with the present system, but they are more of an elementary character, because the student is introduced into his profession too late.

For those theoretically inclined, an opportunity should be offered for studying mathematics, physics, and chemistry beyond the scope necessary for ordinary engineering practice.

THE CONCENTRIC AND THE PRESENT METHODS DIAGRAMMATICALLY COMPARED

The following two diagrams show the difference between the present schedules of instruction and the schedules arranged according to the concentric method. Lighter portions signify the practical side of the subjects, the darker portions refer to the theoretical side.

With the concentric method (Fig. 3) the student begins with the practical side of electrical engineering and with an elementary description of other branches of engineering activity. A considerable portion of time is allotted to general subjects, but practically no time to auxiliary sciences, such as mathematics, mechanics, and physics. As the course progresses, more and more time is devoted to electrical engineering, and less time to other branches of engineering and general culture. The studies themselves gradually become more rigid and theoretical. This naturally requires more and more time to be devoted to the auxiliary sciences. The small light portion in the senior year refers to practical elective studies (specialization).

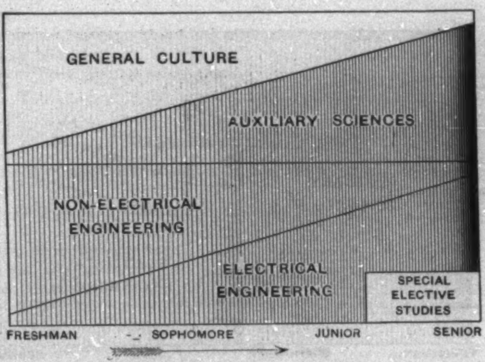

FIG. 3—Arrangement of subjects of study with the concentric method (from practice to theory)

In contradistinction to this scheme, the method now generally adopted is represented in Fig. 4. Here the first two years are practically filled with dry auxiliary studies, and the student does not get even a glimpse of his future profession until his junior year. And when he gets to his profession, the studies have again a theoretical character and only gradually become more and more practical.

A comparison of the two diagrams will clearly indicate the points of difference, and they do not require any further explanation. Those particularly interested in the subject will find these principles incorporated in the schedules printed below.

CONCLUSION

1. The study of engineering should begin in the freshman year and be carried throughout four years.

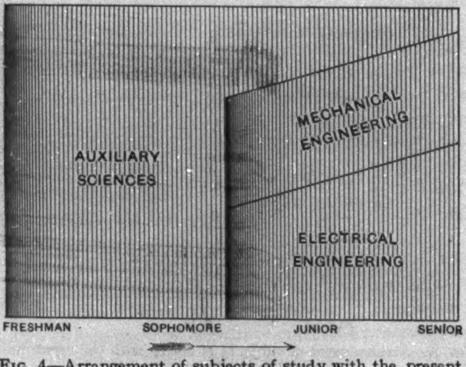

FIG. 4—Arrangement of subjects of study with the present method (from theory to practice)

2. Engineering instruction should be taken up with first giving a bird's-eye view of actual practice, and not with theory.

3. Auxiliary sciences, such as mathematics, mechanics, physics, and chemistry, should not be required further than is necessary for the understanding of engineering, and should be given later in the course.

4. Each year of study should be as much as possible self-contained, the mental horizon of the student being gradually and *concentrically* widened (Fig. 1).

APPENDIX

Proposed schedules of study according to the Concentric Method. The numbers signify the number of hours per week for first and second term.

Freshman year

(Suitable for all engineering students)

	Hours	
Cyclopedia of electrical engineering		2
" " mechanical "	2	
" " civil "	2	
" " mining "		2
Handling machinery	2	2
Making simple apparatus	2	2
Physical culture—one hour every day		
Electives.		
Law, medicine, history, economics, philosophy, languages, painting, music, etc	6	6
Recitations in at least three subjects	3	3
Total hours	17	17

Sophomore year

(For mechanical engineers and electrical engineers)

	Hours	
Descriptive course in electrical engineering		3
" " steam "	3	
Principles of manufacturing		3
Mechanical laboratory	2	2
Electrical laboratory	2	2
Shop	2	2
Mathematics of engineering	3	3
Drawing in connection with laboratory and shop	2	2
Electives (non-engineering)	3	
Physical culture—one hour every day.		
Total hours	17	17

Junior year

(Electrical engineers only)

	Hours	
Electric lighting	2	
Generators and motors		2
Electrical transmission		2
Electrical measurements	2	
Electrical shop-work		2
Electrical laboratory	2	2
Power engineering		4
Machine design	4	
Mechanical laboratory	2	

Mathematics	4	
Mechanics		3
Physics		3
Chemistry	2	
Total hours	18	18

Senior year

(Electrical engineers only)

	Hours	
Electric and magnetic circuits	3	
Alternating currents		3
Theory of electrical machinery	2	2
Laboratory	3	3
Electrical calculations	2	2
Theoretical electives:		
Mathematics Physics Mechanics Chemistry — two subjects to be taken		8
Practical electives:		
Electric railways Telephony Design Power plants Hydraulics, etc. — three subjects to be taken	8	
Total hours	18	18

DISCUSSION ON "THE ATTITUDE OF THE TECHNICAL SCHOOL TOWARD THE PROFESSION OF ELECTRICAL ENGINEERING" AND "ON THE CONCENTRIC METHOD OF TEACHING ELECTRICAL ENGINEERING", AT NIAGARA FALLS, N. Y., JUNE 27, 1907

V. Karapetoff gave an abstract of his paper and said in conclusion: I appear with this paper before the Institute, because of my conviction that the Institute is competent, as a body, to dictate to the technical schools the requirements which their graduates ought to possess. I hope to see the day when the management of the Institute will appoint a committee on technical education. We now have thirteen committees—not a very lucky number—I wish this number could be increased to fourteen and the committee I have suggested be appointed.*

F. B. Crocker: Professor Norris says:

> Electrical engineering is taught as an application of mechanics, the only difference from other branches of mechanical engineering being in the source of the forces and the methods of transferring and transforming energy.

I object to that expression, because it is not true. Mechanical engineering is a fine profession, no one has greater respect for it than myself, but electrical engineering won its independence some years ago, and I think it is a little late to speak of electrical engineering as being a branch of mechanical engineering. Another reason why I object to it is that it leads to unpleasant feelings. Taking another step backward, we find that the civil engineer considers that every engineer who is not a military engineer is a civil engineer. I presume that Professor Norris used that expression in a general way, meaning that we are dealing with mechanical problems; but in the Engineers' Building in New York the mining engineers, mechanical engineers, and electrical engineers are certainly on terms of equality, and I cannot see any reason for subordinating one to the other. It has usually been the custom in the education of electrical engineers in this country to consider electrical engineering as part of mechanical engineering or physics. Nearly all courses of electrical engineering were grafted on, or formed parts of a course in mechanical engineering, or a course in physics. Columbia University, with which I am connected, started a course of electrical engineering in 1889 which was not part of mechanical engineering or of physics. It was as distinct as any other course in the university. We took that stand 18 years ago and have had no occasion to recede from it. I think there is a strong tendency for others to take the same position.

Professor Norris, in his history of the development of electrical engineering education in this country, overlooked the fact that we have courses which are specifically electrical engineering and not appendages to mechanical engineering or physics.

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*Such an Educational Committee has since been appointed.

In Professor Karapetoff's paper, what he advocates is not only very radical, but opposed to the whole history of education, which from the very beginning has dealt first with the simple and later with the complex. When I say "simple", I do not mean necessarily the most easily understood, but the idea involving the fewest things to think of at one time; that is, principles should precede practice. I think this is natural in education. It certainly is the historical method. Furthermore, we have experience bearing upon that point. Take an institution like the Troy Polytechnic, which for many years taught theory almost exclusively with very little laboratory or other practical work, that institution has been successful and has turned out a number of eminent engineers. While it may have modified its course somewhat recently, this experience shows that it is possible to turn out successful engineers on this plan. Perhaps that is going a little too far, but it shows it is possible to do that. On the other hand, the trade-school, which deals with practical matters almost entirely, is very well in its way, but it does not produce the highest intellectual results.

Furthermore, we must have some sort of a *pons asinorum* for weeding out the incompetent men. I think that we should not make it too easy, or too pleasant, to get into the electrical engineering profession. At West Point, for example, the cadets are made to do exactly what they don't want to do. That is what a man should be taught to do. This leading a man by the hand to pleasant places does not meet my approval; in professional education a student cannot learn electrical engineering by sitting in the park and looking at beautiful scenery. That is too easy. A student must be capable of abstraction; he must be capable of self sarcifice; he must do the very thing he does not like to do, and do it well. I consider West Point the best technical school in the world, and in itself a very strong argument in favor of technical education.

I do not agree with the contention that subjects like chemistry, physics, mathematics, and mechanics, should be taught by engineers, especially electrical engineers. I do not object to a teacher having an engineering interest, a man with a high opinion of engineering, but if he is an electrical engineer and teaches chemistry, mechanics, or physics, he will teach those portions which he *thinks* are important. He may be right at the time, but perhaps five years from then the whole situation changes. I believe in teaching chemistry, physics, mechanics, and mathematics for themselves, and not picking and choosing; if properly taught these subjects, the student will be well equipped and can talk on equal terms with other men who have been taught these general subjects.

Gano Dunn: I wish to express satisfaction with the policy of the Institute, developed in recent years, of devoting so much attention to the subject of engineering education. It has been said that the civilization of a nation may be measured by the height of the plane upon which it places its women; it is equally true that the proficiency and accomplishment of a profession is in direct proportion to the attention it gives and the respect it has for its educational influence; to the importance it attaches to its universities and colleges. It was a refreshing address that President Hadley of Yale delivered at the dedication of the Engineers' Building in New York. He said if there was any thing that made the nineteenth century different from all the centuries that had preceded it, it was the accomplishment of the engineer—never before in the history of the world had human beings had so much control over the materials and forces of nature, and the result of that control was transforming all human activities. He went so far as to imply that before long the most successful merchant would be the merchant-engineer; the most successful mayor of a town the mayor-engineer; the most successful statesman, if you will, the statesman-engineer. There is something in the method of an engineer's mind that is direct, that goes straight to the truth, and, although we have been discussing a code of ethics to-day which implies that engineers are not honest, I believe that they are naturally honest because their contact with nature has led them to expect the truth and, when they do not find it, to put the blame on their own methods of investigation. They proceed further with confidence that what they are dealing with is absolute truth, and that if they persist the truth will be revealed. The influence of the engineer is extending to all other callings, and the engineer in the future will exert an influence that he has never dreamed of exerting in the past. Consequently, if we are to grasp the glorious future which has been outlined for us, many of us believe we cannot give too much attention to the methods by which we educate our engineers.

Professor Karapetoff's paper interested me extremely because of his concentric method of instruction. I have little cause for complaining of the methods under which I was instructed, but I feel with Professor Crocker that the plan Professor Karapetoff outlines is too radical. I think, however, that our existing methods could be profitably modified to include many of his ideas. For instance, it would have helped me enormously while I was a student if I had had some person in the capacity of a kind friend at college to give me the relations which the studies I was pursuing bore to other studies and to the activities of the world. Instructors are supposed to do that, but, because each man is devoted to his specialty, very often he does not do it. I really think we could profitably establish in our universities a course on the correlation of the student studies, to which might be given a very small portion of time, but that portion of time would be highly efficient. A student could then know it would be worth while for him to study calculus, for the good it would do him. He could have a promise given, on the strength of which he would work hard.

I believe in America we are ahead of Great Britain in technical education. Conversation with the manager of a correspondence school over there revealed that many of his students were obliged to keep secret the fact that they were studying technical subjects. Many of the industrial managers, I have been told, have not had theoretical educations, and they prefer to employ men who have grown up in the ranks of their business, rather than men who have received a technical training. I even know of one Oxford man who wanted to go to Cambridge to take a technical course, and the superintendent preferred he should go straight from Oxford into the factory, feeling that he would do better than if he took a technical training. I can hardly believe it, but it is true.

I should like to expose my ignorance of the law by giving it a dig in passing. I believe that engineers have set the pace for progressive training, and, as a result the engineering mind, as President Hadley described it, has a great future. We come into contact a great deal with the law in the direction of patents, and in many other directions. It seems to me that progress in medicine, in the arts generally, in all commercial industries, in engineering, and in science has been very great, but that progress has not been as great in the law. The law to-day is more complicated and less satisfactory than it was many years ago, and, while it is perhaps idle to discuss the question here, I feel if the engineer uses his influence, whenever he has a chance, to urge the simplifying of legal processes, and expresses his disapproval to lawyers of the complicated processes which they now pursue, and which many of them advocate, some good may be done.

As between a broad general training in a technical school and a specific training which, of course, must be limited to a few subjects, I prefer the former, and this supports Professor Karapetoff's ideas. A man is better equipped for life if he knows the scope of his field, even though he does not know many specialties in it, than if he is made an extreme specialist in a particular portion of the field which he may not have occasion to use. Not only is he better equipped, because he can realize on his time spent at college, but because his general training has broadened him as a man in a way that the special training would not do. I hope every convention will have some educational papers, and that we will all take pleasure and pride in supporting our universities in every way we can.

William Esty: A number of the subjects brought out at this session seem to me to warrant the adding of some papers on technical education to our convention programs. I agree with Professor Karapetoff that in dealing with young men, say at the college age of eighteen, there is necessity for giving them something concrete to take hold of on which to build up the theory. I think that is the natural order of development in the child; and with college students some attention must be paid to the natural order of their development. Professor Crocker, in discussing this matter, spoke of beginning with principles because they were simpler than the concrete cases. It seems to me that his idea contradicts the view of Herbert Spencer, who speaks of principles as being a conglomeration of concrete things and of a principle or law being essentially more complex therefore than any one of the concrete facts on which it is based. It seems to me that that is a valid definition of a principle—an aggregation of concrete facts which have finally been formulated into principles from experience. Principles then are more difficult to teach to a freshman than isolated concrete facts: so I think we should have something of the concrete to give him also.

I am going to outline briefly how at Lehigh University we try to accomplish the object of giving the students an idea of some of the concrete facts on which engineering is based, and at the same time give them some theory also. At the end of the freshman year the mechanical and electrical engineers take what we call our "summer school in constructive elements of mechanical and electrical apparatus". The summer school lasts only four weeks, and the students are at work for three hours in the morning and three hours in the afternoon. In that rather brief time we attempt to acquaint them with the elements of mechanical and electrical engineering. For instance, in the electrical end of it, in which I am especially interested, we have them dissect circuit-breakers, rheostats of different types, disassemble motors and generators, lightning-arresters and transformers, and sketch the circuits. We do not attempt at first to teach them the complete theory on which all this apparatus is based, but rapid progress results by having them acquainted with the actual things. We find this plan very advantageous. We have tried it now for six years, and if there is anything in the old adage that, "the proof of the pudding is in the eating", we can show that this pudding has proved good with us. We find, as a matter of fact, that the mechanical and electrical engineers who have taken this supplemental course in concrete facts, with a little theory mixed in on the side, are much better able to grasp the theory of the dynamo and of the transformer later on in their course than are, for example, the civil engineers who do not have this summer school work. We find it saves time in the long run. Our object is to concentrate in that four weeks an experience with the things themselves that these young men might take a year or more to acquire without it. I am not sure whether we are unique in this respect among colleges and universities, but if there are any others that have had similar experience I should like to hear from them.

In summing up this controversy of theory versus practice, it strikes me that it is after all another phase of the old question as to whether we should have classical education or technical education and as to which does the most for the young man. We have heard this thing wrangled over now for twenty or thirty years, and the end is not in sight. I think both sides of the controversy can certainly come to a common ground if we conclude that what after all is the object of education is the training of a young man to think for himself, and that implies, of course, a knowledge of how to solve problems when they arise. We cannot possibly teach all problems to a young man in college, but we must ground him in fundamental principles, giving him theory even at the expense of practice, so that when he leaves college he will have training which will enable him to solve almost any problem. That, I think, is the aim of technical education.

G. W. Patterson: As a member of the committee of the University of Michigan on reorganizing our course, I have taken part in a great many consultations as to what a technical school course should include. I must admit that the trend of the work by our committee has been entirely away from what Professor Karapetoff has given us to understand is his notion of the proper thing. We feel that a man who goes to a technical school is a crude product, and that there are many things which he ought to study to make him an educated man before he takes up engineering as a specialty. Without modern languages, without drafting, without a thorough grounding in mathematics, physics and chemistry we feel no man is competent to understand the elements of any kind of engineering, to say nothing of electrical engineering. I am of the opinion that there are some germs of truth in what Professor Karapetoff has told us, but if we examine his paper closer we find that if we adopted his ideas we would in my opinion make a sort of plaything of engineering. Instead of a real training, which should be given to men who are to occupy these important positions, the actual training would fall far short. The engineer should be an educated man; he cannot be educated in a specialty that ignores the elements which go to make a broad education. With us the trend is rather toward a six-year course than to cut off the things which we find necessary to teach in the first year or two under the present plan. In the University of Michigan we have six-year combined courses in which a man registers in the department of literature, science, and the arts, and also in a professional department. At the end of four years he receives the degree of bachelor of arts, and at the end of two years more either that of doctor of medicine, or bachelor of laws. In the engineering department the trend is toward the same thing; that is, a longer course in which we do not cut out the modern languages, or reduce the amount of physics and chemistry in the period of training, but put them in earlier and put in other things. There should be no opportunity for a man to learn engineering without a proper foundation. Omitting the foundation, is like trying to build a mansard roof first and put on the foundation the last thing.

If Professor Karapetoff's paper be taken seriously, it would, I think, tend to destructive rather than to constructive teaching.

Lester W. Gill: I am interested in this subject, because I have been endeavoring for the past few years to develop a course in electrical engineering in one of the Canadian universities. I am in sympathy with a number of the opinions expressed, but I do not think that it is practicable to introduce the radical changes suggested by Professor Karapetoff. Referring to his proposed schedule, it is noted that mathematics is omitted entirely from the work of the first year, and very little is set down for the second year. My experience has been, not only in my own case but in the case of students in my classes, that if mathematics is dropped even for one year before the student is acquainted with its practical applications, he loses his grasp and consequently his interest in the subject. To most students mathematics is a dry subject unless it is presented in an interesting way; but even admitting that many find it uninteresting, it involves a certain amount of discipline which is quite necessary.

I quite agree with President Sheldon that the greatest difficulty lies in the presentation of the subject, and in my own work I have endeavored to make the elementary subjects practical as well as theoretical. This results in a compromise between the standard college schedule and that proposed by Professor Karapetoff. In this way the elementary subjects—mathematics, physics, and chemistry—can be made as interesting as the purely engineering subjects. As a student I found mathematics the most interesting subject of the whole course, because the teacher knew how to make it interesting. To make these subjects interesting the student should be given examples of the practical applications of the subject as he proceeds, and these examples should deal with things with which he is familiar. This arouses his interest in the theoretical side of the subject and he at once realizes its value. As an illustration, take the case of a student in physics trying to master Ohm's law. If this is presented to him merely as an abstract natural law, he will not find it very interesting, and will consequently get only a superficial conception of it; but give him an illustration of its application; ask him to calculate the voltage at the end of a given trolley line, given the distribution of current, and it will be found that after solving this problem he will look upon this law from an entirely different standpoint.

The above illustrates what I mean by making the elementary subjects of a practical nature. My own opinion is that the weakness in our engineering schools lies in the method of teaching rather than in the arrangement of the schedules. The aim of the teacher should be to develop the student's ability to reason for himself, to think logically rather than to memorize rules. When a student can take the initiative and reason things out for himself, the technical school has done all it can to make him efficient from a technical standpoint.

L. D. Nordstrum: Referring to Professor Karapetoff's paper —this proposed method is in a sense radical, but I cannot help but agree with him in part. I do not think that the students should have mathematics and physics and kindred sciences taught by engineers. It is well if we can have mathematicians introduce as far as possible the engineering subjects, so as to make them interesting to the student, but for the teaching of these subjects thoroughly we must have a professor of mathematics and a professor of physics, etc., who are, so to speak, specialists in that line. The time is here when the trend is towards specialization, and no man can hope to have the strength of a thorough mathematician, a thorough physicist, a thorough engineer, etc., all in one. The student must get these from individual instructors who devote their entire time to their particular subject.

I believe that we can not expect to turn out a finished engineer from our universities. I think all that we can hope to do is to take our student as he enters the college and direct and train his mind properly in the fundamental principles, giving him a good foundation upon which to build. I think it is too much to expect a student in a four years' course to gain all that is gained and can only be gained in the practical pursuits of his profession. It is my opinion that a man has never finished his education; his entire life is that of a student. His university years are merely the starting or foundation years.

V. Karapetoff: In reply to Professor Crocker's remarks, I would say that, of course, the instruction should proceed from simple to complex; the point at issue is what to consider as simple and what as complex. This to my understanding varies with time. Twenty years ago it would not have been simple to begin the freshman year with instruction in street-car propulsion and incandescent lamps; but now this is much simpler for the student than an instruction regarding the properties of magnetic poles. We now see street cars and electric lights much more than magnetic poles. Professor Crocker mentioned trade-schools, and I understand him to favor the opposite, or the theoretical courses. I am not in favor of the trade-school idea, or of a theoretical-school idea. I am in favor of the *psychological* idea. Our president and some other speakers compared the student with raw material; there is however a great difference between raw material in a manufacturing sense, and a man. A man is a thinking being, and if you try to make a machine out of him, he kicks at first, and then withers intellectually. The analogy to a machine should not therefore be carried too far.

Mr. Dunn said that my method is very radical. Perhaps it seems radical for electrical engineers, but it is not considered radical at all among our best educators. It is an already acknowledged fact among our primary and secondary schools. I simply transplanted the psychological ideas that are in use in the primary and secondary schools in this country, schools of which we have good reasons to be proud. With me it is primarily the question of assuring a coöperation of the student. If you do not agree with teaching electrical engineering in the freshman year, there still remains this point—that the coöperation of the student is not secured with the present method of instruction. Hence, you must change your method so as to secure his coöperation. He is a thinking being, he is supposed to enjoy his life while in school, and not simply live in expectation of the things which may come after he has left the school. Professor Crocker thinks that unpleasant things must be connected with the education of young men. I agree with him, and wish to assure him, that even with the concentric method there will be enough left to make the life of a student more or or less unpleasant. Professor Crocker objects to mechanics, physics, mathematics, and chemistry being taught by engineers from the engineering standpoint. Surely they should not be, at the *advanced* stage, but at the elementary stage, in order to connect them with the engineering profession. In the courses of studies which I give in my paper, I propose that mathematics and mechanics should be taught in the second year by an engineer.

Expository ability and the raising of salaries of professors have been said to be more needed at present than a change in methods of instruction. I do not quite see how the concentric method could prevent a raising of salaries, or affect the necessity for expository ability on the part of the teachers.

Professor Patterson thinks that I am opposed to general culture. On the contrary, if you will kindly look into my courses of instruction you will find a considerable amount of time devoted to general culture in the first two years. I do this not only for the sake of general culture in itself, but also in order to give the student an opportunity to select intelligently his profession, before he goes into the details of it. This is more important than the general culture, as now understood. It is time to stop calling a study of mathematics and mechanics or even languages in their dry, abstract form, as "general" culture.

In presenting this paper I had in mind two purposes: to criticize the present system of instruction, and to give a new, improved method. Even if the concentric method is no good, there still remains for you to answer the criticisms against the present system, and to develop a better system.

Charles F. Scott: There are some dozen points which I had in mind to bring up, but I will forego doing so at the present time. I will refer to one point, however, the statement made a little while ago that the method proposed by Professor Karapetoff would be opposed to the whole history of education. Is not that one of the best recommendations it has? Has not the history of education for the last fifty years been one of advance? Not long ago new sciences were proposed instead of old languages. Then science was degraded by being applied to engineering. Then engineering ceased to be theoretical, and laboratories and machine shops found their way into colleges. Educational ideals and methods have been changing. We have not reached perfection. Engineering methods must be applied to the teaching of engineering, and that means development. Possibly, therefore, one of the best recommendations of this proposed system is that it is radical and is opposed to old ideas. If it is not quite the right thing it is getting closer to it and it merits careful consideration.

I wrote down two words on this slip of paper a moment before Professor Karapetoff mentioned the same words "educational committee." Accepting the suggestion of Professor Karapetoff as a motive, I am very pleased to second that motion; namely, that the Board of Directors of the Institute be requested to consider the advisability of the appointment of an educational committee.

V. Karapetoff: I shall be very glad to make such a motion. (The motion was put and carried.)

J. J. Carty: A few years ago I would have been quite ready to submit a number of criticisms on our technical schools. But the more information I get upon the subject and the more attention I pay to it, the more difficult it seems to be and the less ready am I to criticize. During the past twenty years I have received into my office a very large number of graduates from the principle technical schools in America, and from this experience I am able to make two generalizations. They are these:

1. That the best men do not all come from one school. The personal equation is so overwhelming that so far as my experience goes, the efficiency of the school from which the men graduate cannot be determined by the relative efficiency of the men themselves after graduation.

2. As a rule, the men are well trained technically but are very often defective in respect to that broad and liberal training which should underlie the technical education of every professional man. This defect is a serious one and very difficult to overcome. I have almost come to the conclusion that it is hopeless to attempt to give in the technical school the necessary broad and liberal foundation studies, and at the same time keep up the arduous work required of the student in connection with the strictly engineering studies. I am coming to the state of mind where it seems to me that the introduction of these so-called broadening studies into the curriculum of the technical school might fairly be likened to the introduction of such studies into a medical school.

As the general scheme of education in this country stands at present, I think that the electrical engineer, for the foundation of his liberal education, must depend solely upon the scientific studies themselves, or pursue his broad studies either before or after his technical course. Helpful as the scientific course is in the development of the student when forming part of a liberal education, it alone is not sufficient if the engineer is to take his place in the world, as he should, with cultivated men of affairs, whether they be physicians, lawyers, or men of business. The engineer should be so equipped that he may attain those ideals so well set forth by President Hadley in his recent address at the dedication of the Engineers' Building, in which he says:

> We have outgrown the day when a little common sense was sufficient for managing the affairs of the nation. They are become too complex, and this complexity gives the engineer—if he will add to his training in mathematics a training in ethics and political economy and the fundamental principles of the law—an opportunity such as never before existed to claim and receive the position which rightfully belongs to him.

Further on in his address, President Hadley says:

> We celebrate to-day and we are justified in celebrating the recognition of science as a necessary guide in the conduct of the material affairs of each man's business. Half a century hence, when our descendants shall meet in this building, or some yet greater building, I am confident that they will celebrate a yet greater thing—the recognition of the right of men of science to take the lead in enlightening the thought of the people on public affairs and the responsibility of filling the higher positions in the service of the commonwealth

President Hadley says elsewhere in his address that the course of our technical schools tends to have a narrowing effect upon the student, instead of a broadening one. This is in my judgment often the case. The narrowing effect of this technical training, it seems to me, is a negative one, not due to the technical course *per se*, but due to the fact that technical training is given, to the exclusion of liberal studies. I am hopeful that ultimately our entire scheme of school, college and university training will be modified so as to permit the student to graduate from his professional school at a sufficiently early age, and at the same time have received the necessary liberal education. At present I do not see how this can be done.

How to provide this broad and liberal education and at the same time not encroach upon the legitimate work of the professional school is what I consider to be the problem of engineering education to-day. Until this is settled, I have very little heart in any discussion, such as that pertaining to the relative number of hours which the engineering student should spend in the laboratory, at shop work, or at lectures. Once the engineering student has a proper educational foundation to build upon, his professional studies can no longer be said to be narrowing, for these studies would, in the light of a proper philosophy, take on a new meaning. They would become an absorbing, intellectual pursuit rather than a hard and disagreeable task. They would become to a high degree broadening.

With this large question out of the way, I am satisfied that the problem of the make-up of the curriculum of the engineering school could be satisfactorily solved. If these views which I have expressed should prove to be correct, we would still have before us the most difficult question as to what broadening studies should be specified, and that perhaps equally difficult question as to where and when these studies should be pursued.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907.

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REGENERATION OF POWER WITH SINGLE-PHASE ELECTRIC RAILWAY MOTORS.

BY WILLIAM COOPER

The conditions necessary in order that an electric motor may operate successfully in regenerating or restoring power to the supply circuit are:

1. The counter pressure generated by the motor must be greater than the impressed pressure of the supply circuit.
2. The value of this excess counter pressure must be under control and maintained in suitable relation to the impressed pressure.
3. There must be at the time other power-consuming devices connected to the supply circuit.

There is no difficulty in producing the first condition the second is the one that is difficult to fulfil. There are two methods of regulating the counter to the impressed pressure; one is to increase the counter pressure and the other to reduce the impressed. The third condition, except in isolated cases, will be taken care of by the operating load.

Practically all variable-speed railway motors are of the so-called series type, and as this type of motor is the only one having the proper characteristics for general railway work it alone will be considered. The operation of a series dynamo electric machine as a series generator on a constant-potential circuit is a problem which many have grappled with, but none has solved. The machine must be given a shunt characteristic of a greater or less degree in order to make such operation possible. A machine having the shunt characteristic predominant is unfit for use as a railway motor, and as this characteristic must be predominant to operate successfully as a generator it is at once evident that the motor must be changed in some manner before it can be used as a generator. But this is not the only condition which the motor must fulfil in order to operate successfully as a generator in restoring power to the supply circuit; the motor must operate satisfactorily while the armature current is varied through a wide range with a constant field. This is evident from a very casual observation of the conditions.

Assume that the car or locomotive being driven by the motor under consideration has attained a balanced or free running speed under the conditions. The motor is then developing only sufficient torque to overcome the train resistances. The motor, being a series machine, has the same current in the field and armature. Under these conditions a very slight increase in the field current would increase the counter electromotive force of the armature to a value greater than the impressed electromotive force of the supply circuit.

Now assume an ordinary series motor in which the armature current cannot be increased materially above the corresponding field strength without disturbing the commutating conditions; it follows that the motor acting as a generator can only give a retarding force approximately equal to the train resistances. This added to the train resistance would give a total retardation so small that it could not be called a braking effect. From this it is obvious that the armature current must exceed the field current at times in order to produce a retarding effect which can be utilized in bringing the train to rest, or in holding the train on a grade. This, then, is another condition which the ordinary series railway motor does not readily fulfil.

From the foregoing it would seem that a motor to operate successfully as a regenerator of power must have the following characteristics:

1. It must be capable of operating through a wide range of variation between field and armature current, and

2. It must be provided with some means of producing a shunt characteristic.

The first characteristic exists to the fullest extent in a motor having some means of compensating for armature reaction, as well as a means of maintaining a constant commutating condition. This characteristic also exists to a limited extent in a motor having either one of these functions.

The second characteristic is not so easily provided. In the direct-current motor it can be obtained by providing the motor with both a shunt and series winding, either of which has sufficient capacity to operate the machine either as a shunt-wound generator or as a series motor.

Another method of furnishing the shunt characteristic is to provide a means of separately exciting the motor field independent of the line or motor voltage. There are several ways of doing this. In the case of four-motor equipments, one method is to use one motor as a generator to excite the other three motors which will operate as generators, being connected to the supply circuit.

Storage-batteries may also be used to excite the fields, but this arrangement has its disadvantages in being complicated.

The great difficulty encountered in operating direct-current motors as regenerators of power is that the impressed pressure is a constant, and the means at hand for meeting it are very limited. As the ordinary series motor will not permit of any very great variation of armature current with a constant field, and as only a very limited number of combinations of the motors is possible, the range through which an equipment can be operated regeneratively is, under the most favorable conditions, very limited.

In the single-phase, alternating-current motor of the series type these necessary characteristics are inherent. Without entering into a description of this motor, the design of which is well known, it is sufficient to say that the machine is provided with a compensating winding to neutralize the armature reaction, and also has preventive leads between commutator and armature windings which assist in commutation. This construction yields the first characteristic; the second is easily obtained in connection with the transformer used in the voltage control of the motor.

The method of producing this result is to use one of the motors of the equipment as an exciter for the others. By providing the transformer with suitable voltage taps, the value of the field current of the exciter may be varied through a wide range, as well as the generated voltage of the restored power. In this respect the conditions are very much more favorable than in the case of the direct-current motor, in which the only variations that can possibly be made are in the series-parallel combinations of the motors that are being used as generators.

The exact arrangement of the motors and their connections are shown diagrammatically in Fig. 1.

Assume the car or locomotive upon which the motors are mounted to be in motion, the armatures turning at a corresponding speed. If the field of the first machine be connected to the transformer, an alternating electromotive force will be generated by its armature, the value of which will be directly proportional to the speed. If the field of the other motor be connected to the exciter armature, an alternating current will pass through it, and the second armature will in turn generate an alternating electromotive force the value of which varies about as the square of the speed—the excitation of the first machine remaining constant.

The electromotive force generated by the second armature will bear a very close phase-relation with the electromotive force of the transformer, for the reason that the current in the field circuit connected to the transformer lags approximately 90°, as does the current in the field-circuit of the second machine. This combination throws the generated electromotive force of the second machine approximately 180° back of the transformer electromotive force, or, by reversing the connections, in the same phase-relation.

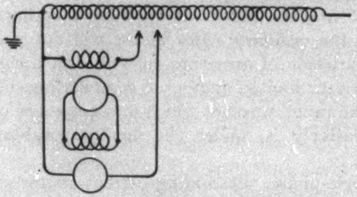

Fig. 1

The phase-relation between the generated and transformer voltages is shown in Fig. 2.

This record shows that the two electromotive forces are in exactly opposite phase. Under these conditions the current flowing after the circuit is closed with the connections reversed, will be displaced from the electromotive force, due to the impedance of the armature circuit. Fig. 3 shows this displacement when the armature is carrying about 100% current overload.

This is at a power-factor of 80%. The power-factor varies between this and 100% as the load decreases to zero. The obvious method to improve the power-factor is to shift the phase-relation of the generated to the line electromotive force. The result of this is shown in Figs. 4, 5, and 6.

Fig. 4 shows approximately the relation of the generated to the transformer electromotive force as it would be on open circuit, as the current in this case is small.

From these records it is evident that there is no difficulty in restoring power with a single-phase, commutator-type motor at practically 100% power-factor, the machine operating as a non-synchronous, alternating-current generator.

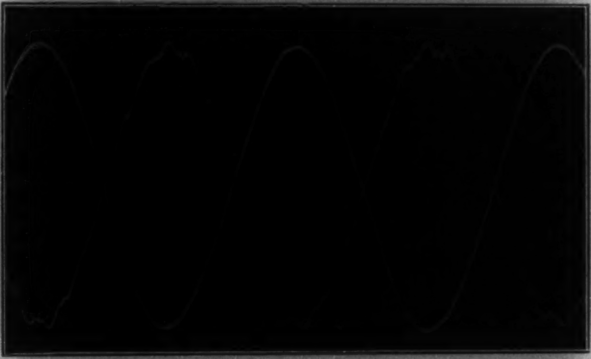

Fig. 2—Oscillogram of generated and transformer electromotive forces. The generated electromotive force is the curve with the irregular top

This condition being established, the next step is to see how it applies to actual operating conditions. From the foregoing it is evident that one of the motors of the equipment must be set aside for use as an exciter for the others, or a separate motor-generator set must be provided. If a separate source of excitation is provided, all the motors can be used to the fullest extent for regeneration of power, in which case the total capacity for regeneration will be increased over the capacity of the machines as motors by the increase in the power-factor. If the regenerative function is to be used for braking in making frequent stops, it might be desirable to supply the separate excitation; but if it is to be used in holding the train on grades it is unnecessary, as the remaining motors, if the equipment consists of three or more motors, will have ample capacity to do the work.

Assume a 2% grade of considerable length. The motors, all working, have sufficient capacity to haul the train up the grade. Assume the equipment to consist of four motors. Assume train resistances at six pounds per ton. The total tractive effort will then be 46 pounds per ton in ascending.

To hold the train at the same speed in descending. a retarding force of 34 pounds per ton must be supplied. The retarding force necessary is then approximately 75% of the force necessary to haul the train up the grade. It is evident from this that three of the four motors have ample capacity to exert the necessary retarding force, even if the power-factor of the machines as generators is no better than when they are operating as motors. It has been shown that the power-factor when operating as generators can be made better than when operating as motors; therefore, there is a surplus of capacity in four-motor equipment, and in three-motor equipment about an equal capacity.

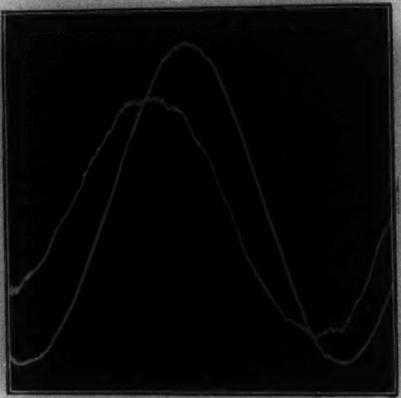

FIG. 3—Oscillogram of current and electromotive force of generator. The lower curve is the current. Power-factor 80% lagging current

The characteristics and capacity of the machines being

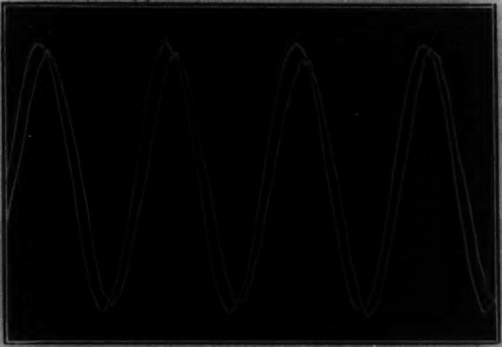

FIG 4—Oscillogram of current and electromotive force under light load. The lower curve is the current. Power-factor 98% leading current.

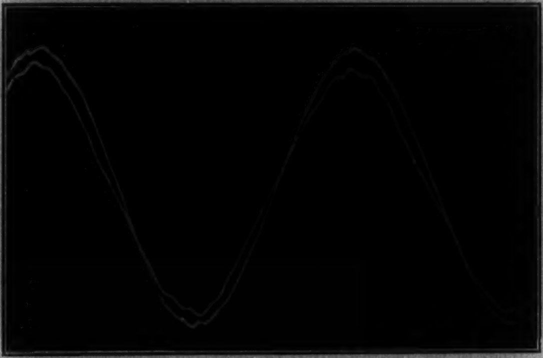

FIG. 5—Oscillogram of current and electromotive force under normal load. Conditions same as Fig. 4 The lower curve is the current. Power-factor 99.5% lagging current

correct for the work, it only remains to provide suitable means for manipulating the circuits to adapt the apparatus to the conditions. This is accomplished by providing switching apparatus to connect the motors in the proper relation and for furnishing and controlling the field current of the machine used as an exciter.

Fig. 7 shows diagrammatically the main circuits and connections for a four-motor equipment. From this it is evident that the switches used must have a current capacity the same as the motors, for there are four in parallel on the transformer and the switches used for reversing carry the current for one motor only. As shown, 36 switches are required for the entire control of the motor equipment.

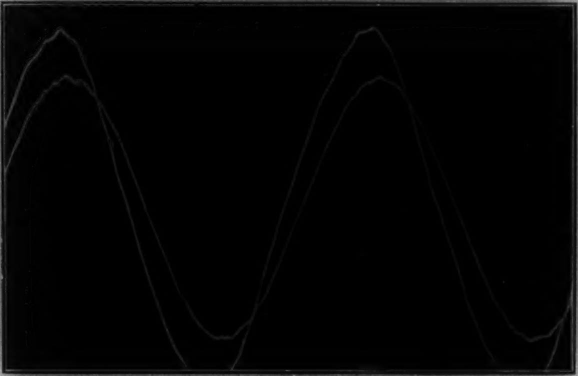

Fig. 6—Oscillogram of current and electromotive force under 100% overload. Conditions same as Figs. 4 and 5 .Power-factor 97% lagging current. The current is the upper curve.

Fig. 8 shows diagrammatically the same motor equipment arranged for regeneration in addition to the regular motor control. As shown, 54 switches are required of the motor-current capacity, and 16 of one fourth that capacity. Of the added switches of the motor-current capacity, 10 have been added to the transformer to enable slow speeds on regeneration to be obtained, and 8 are required to change the combinations of the motors. Besides the added switches, three small preventive coils and a few additional transformer taps are required. From this it is seen that the amount of additional apparatus required is insignificant compared with the result accomplished.

The curves shown in Fig. 9 give the relative tractive and retarding effort, both continuous and maximum, of a four-motor equipment.

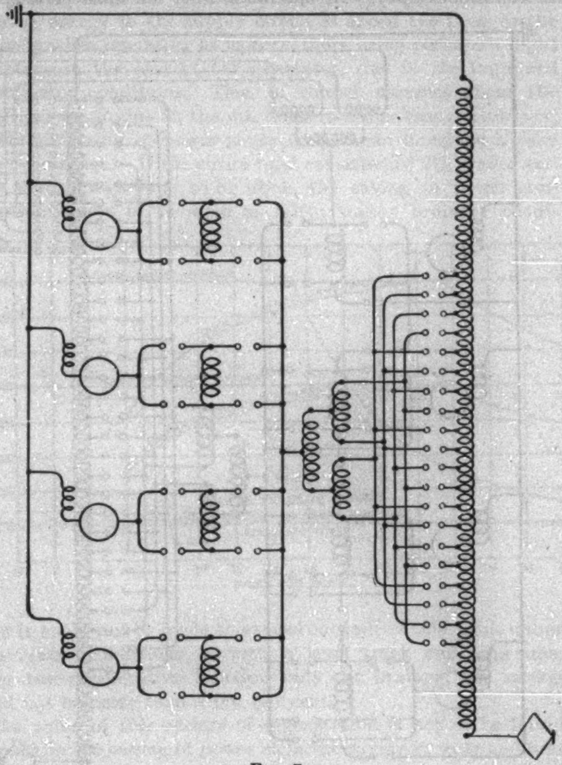

Fig. 7

As shown by the curves in Fig. 9 the three motors of a four-motor equipment acting as generators restoring energy to the line will let a train down a 2% grade at any speed from 9 miles per hr. to 30 miles per hr., that the motors have capacity to haul up the same grade at any speed up to 18.5 miles per hr. This is for continuous duty. At maximum duty for short periods the capacity is increased about 60%. Between 9 miles per hr. and 30 miles per hr. there are 40 operating speeds, the gradations from one to the other being such that at no time will there be any variation exceeding 10% in torque. This necessitates, of

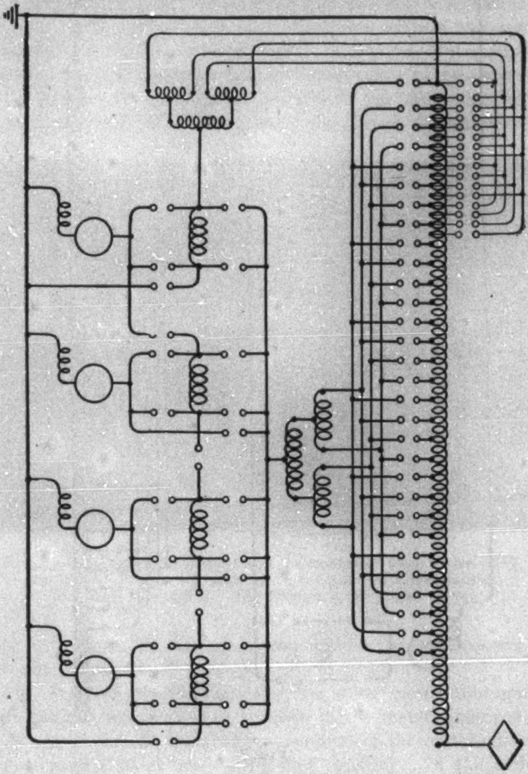

FIG. 8

course, a rather large number of switches being used, but it seems to be a very desirable condition to fulfil in heavy freight traffic.

Efficiency of this system of regeneration. The efficiency of the system when the motors are operating as generators and restoring energy to the supply circuit is about the same as the efficiency when operating as motors, there being perhaps a slight advantage in the case of the generator, due to the improved power-factor conditions. This, of course, assumes about the same load conditions on the machines in either case. However, the actual saving in power-house output can never be a very large percentage. If the entire road consisted of 2% grades and there were no switching to be done, the saving in power consumption might be as high as 50%; under ordinary conditions it could not be made to exceed one half of this, while under unfavorable conditions or with a level track and long runs, using the regenerative function only for braking, the saving could not be more than a few per cent.

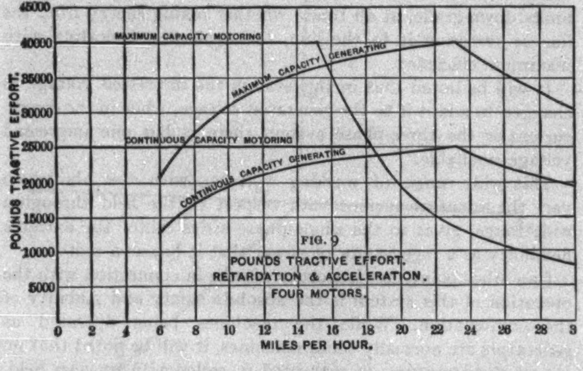

FIG. 9
POUNDS TRACTIVE EFFORT.
RETARDATION & ACCELERATION.
FOUR MOTORS.

The value of this system of regeneration is not to be found so much in the saving of power as in the saving in wear and tear and the ability to operate over a wide range of speed, as well as the comparative safety of operation. In the case of running heavy trains down long grades, the braking apparatus of all cars in the train can be held in reserve, it being necessary to use it only in emergency or in making the final stop. Under these conditions the number of accidents due to the failure of the brakes would be very much reduced.

This is the only system of regeneration yet developed which can be operated at maximum efficiency over a wide range of speed. In the case illustrated, forty speeds between 9 miles per hr. and 30 miles per hr. are obtained. This number can be increased if desired simply by the addition of a few switches.

The three-phase system is the only other one in which the regenerative function has been developed to any extent, but at most there are only a few widely separated speeds at which it can be operated efficiently. Generally there is but one.

A system of electric traction in which the trains must go up-grade and down-grade at one fixed speed in order to operate efficiently is certainly at a disadvantage when compared with one in which the trains can be operated at *any* speed *below* a certain maximum speed up-grade and at *any* speed within safe limits down-grade, at all times, whether taking energy from the line or restoring it to the line, the apparatus operating with maximum efficiency.

It will be noted that in this system the impressed voltage is changed to adapt it to the generated voltage, while in the direct-current or the three-phase system there is but one impressed voltage available.

This wide range of working voltage, with the ability to vary the armature current with respect to the field through a wide range, gives to the single-phase series motor the extreme flexibility as a regenerator of power that it has as a motor.

One other point that is worthy of note in connection with the operation of this system is the absolute safety and stability of the combination. While the machines being operated as generators are normally series machines, it will be noted that no one of the armatures is connected in series with its own field, and under no condition can there be any surging or building up of load. In case of momentary interruption of the supply circuit, the circuit again being restored the system will again operate exactly as before the interruption, there being no surging or violent action of the machines.

The system of regenerating power here described has been used in testing locomotives to give a dead-load condition under a wide range of speed.

Numerous stand-tests have also been made, so that the operation of the motors under the conditions is well established and there is no doubt about the scheme doing all that is claimed for it.

DISCUSSION ON "REGENERATION OF POWER WITH SINGLE-PHASE ELECTRIC RAILWAY MOTORS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907.

W. I. Slichter: The possibility of regenerating power with single-phase motors is one of the valuable features of the single-phase system and one which will be of great assistance in bringing the motor into the field of heavy railway work. The possibility of regenerating at various speeds is well illustrated in Mr. Cooper's paper, but it is interesting to note that there are two points in the system at which the speed can be varied; first, by changing the tap on the transformer from which the exciting motor obtains its excitation; secondly, by changing the tap on the transformer to which the generating motors are connected. These two actions may be independent, giving twice as many steps as there are taps. With this arrangement a very large number of taps on the transformer is not necessary.

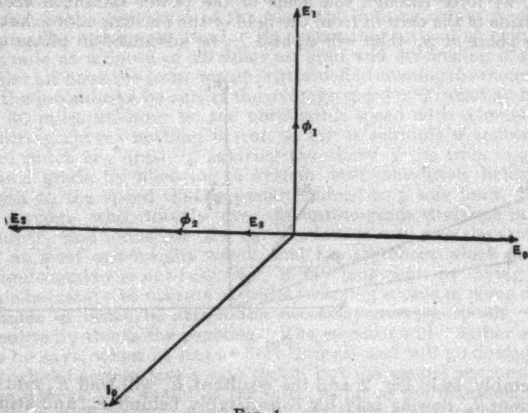

FIG. 1

With regard to the phase of the current which is returned to the line, there is liable to be a low power-factor, due to the inductance in the motor, the line, and the steel rails. This can be improved by a compounding effect in the motor which is acting as a generator, as shown in Figs. 1 and 2.

E_0 represents the electromotive force of the line, or at the secondary of the transformer, which is impressed on the field winding of the motor that is acting as an exciter. The flux which is set up in these fields will be displaced approximately

90° behind E_0, as at ϕ_1. The armature of the motor used as an exciter revolves in this flux and produces a voltage in phase with ϕ_1, as shown by E_1.

This voltage being impressed on the separately excited fields of the power motors, produces a flux in their fields displaced 90° behind E_1, as shown by ϕ_2.

The electromotive force generated by these armatures is in phase with ϕ_2 as E_2, which is nearly in opposition to the line voltage E_0, giving a resultant electromotive force E_3.

This resultant forces the current I_0 through the windings of the motor and transformer, in which there is a considerable amount of inductance, and the current will lag behind E_3 an amount depending upon the inductance of these circuits.

If, however, in addition to the magnetizing current caused by E_1, we force through the fields of the power motors a certain portion of the current from the field of the exciting motor having the phase of ϕ_1, then will ϕ_2 and E_2 be advanced in phase considerably, as in Fig. 2, and the resultant E_3 will lead E_2 and the current I_0 flowing may lag considerably behind E_3, and still be nearly in phase with E_2 or E_0, assuming a position between the two giving a good condition for returning power instead of volt-amperes to the line.

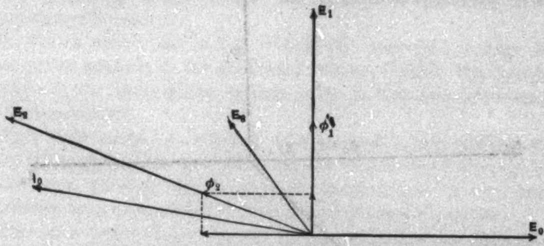

FIG. 2.

L. B. Stillwell: The importance of recuperation has not been recognized adequately by American railway engineers. Its importance, as Mr. Cooper states, is primarily due to the fact that it assists powerfully in reducing wear and tear of rolling stock equipment. The average cost of renewals of rolling stock of the railways of the United States to-day exceeds $250,000,000 per annum. Of that total, a large proportion, probably at least one-half, is due to the destruction of rolling stock by loss of control on heavy grades and by excessive wear and tear of wheels and brakes and strain of draft-gear. A number of years ago when the late Judge Cowan was president of the Baltimore & Ohio, this wear and tear of rolling stock loomed up in the road's cost of operation as so formidable an item that he and some of his assistants very seriously considered the problem of utilizing electricity to operate the heaviest of their mountain grade divisions. Messrs. Duncan & Hutchinson made an investigation and report at that time, and I recall that subsequently Judge Cowan expressed to me the opinion that the saving in cost of maintenance which could be effected by using the three-phase system on this division was of the greatest importance.

In this connection, the work that Mr. de Kando and his associates of the Ganz company have done is of great interest. The argument which Mr. de Kando uses in meeting the opposition of the railway operator, who is of the opinion that it would be quite impossible to operate up grade and down grade at uniform speed, is interesting. Mr. de Kando takes the position that the true limitation of speed, either in climbing or descending a mountain grade, is the curvature of the road, the limiting curves properly fixing the maximum speed. He argues that instead of climbing a grade at a speed of 20 miles an hour and descending it at 40 miles an hour the same result is attained in crossing the mountain if the locomotive be run at the average speed of 30 miles an hour. If 30 miles an hour be the permissible speed with reference to limiting curves nothing is lost, so far as schedule is concerned, and much is gained in assuring the safety of the train in going down grade by adopting a system that absolutely holds the train to the speed that is predetermined as a safe limit.

Anyone who travels over mountain-grade divisions in this country and looks out of a car window usually sees the remains of at least one freight wreck, and the argument which Mr. de Kando makes is not fully met, in my judgment, by saying that it is necessary to operate at widely varying speeds in going down grades in order to attain the necessary average speeds. Undoubtedly this is the practice. The engineer will " let her out ", as he says, when he has a short tangent and will go downgrade at what he considers a safe speed, but the results are shown by the wrecks. It would be far safer, as far as the maintenance of rolling stock is concerned, to fix the limit speed for him in the office of the superintendent and provide a system which does not permit him to exceed the limit established.

As regards the interesting system of recuperation of power which Mr. Cooper has presented, I would suggest that the attempt has been made to go too far in obtaining variation of speed at the price of complication of switching apparatus. In my judgment it would be better to establish a narrower range of speeds for operation on mountain grades, and eliminate a considerable proportion of the switches illustrated in the diagrams. A tendency of single-phase equipment is toward an inordinate use of switching gear.

Recuperation involves, in general, an increase in the output of motors, since they are worked down grade as well as up grade. Probably in practical operation the difference would not be very material in respect to this point. It is customary now to add a second engine when a train reaches the foot of a mountain grade, and in general it would not greatly handicap mountain operation if the second locomotive were to accompany the train over the entire grade, being used to assist in holding back the train and restoring energy to the line in descent. Substantial compensation for the additional locomotive mileage involved would be obtained in the saving of power.

J. C. Lincoln: Has Mr. Cooper made experiments to determine how much more wear there is on the gears of this regeneration system than with the ordinary method now used in operating railroad motors, where the motors are used as motors only and never as generators?

William Cooper: As to the wear on the gears—of course that is purely a mechanical matter and it is self-evident that if the gears do work they will wear. The best example of that, I think, would be the traction brake on street cars, where the electric brake is used for traction purposes. In that case, of course, we find that the gears wear out faster than they would if only used as motors. They are bound to do that from the nature of the case. The amount of wear would be proportional to the amount they are used for regenerating purposes.

Mr. Stillwell's comment about the number of switches involved as shown in the diagrams needs a reply. Of course there are some other considerations which will determine how many switches are necessary, but from the standpoint of making assurance double sure, and having a system to operate without a hitch of any kind from a designer's standpoint, I incorporate a sufficient number of switches to cover any condition. Probably a case would arise where a very much smaller number would answer the purpose.

In regard to Mr. Slichter's point about shifting the phase relation of the generated electromotive force, I ask how he would produce the displacement of the electromotive force on the exciter field? It is simpler to displace the current in the exciter armature circuit than it is to displace the current in the field circuit of the exciter. That can be done by methods well known to the art of shifting the current in an alternating current system, by increasing resistances or inductance to get any predetermined relation.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907.

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FRACTIONAL PITCH WINDINGS FOR INDUCTION MOTORS

BY C. A. ADAMS, W. K. CABOT, AND G. Æ. IRVING, JR.

For several years past some of our large manufacturers have used fractional pitch windings, for induction motors to a considerable extent, and for alternators to a lesser extent.

It was the original purpose of this investigation to develop by theory and experiment a method by means of which the effects of such windings may be calculated; and although this purpose has been successfully carried out as far as time allowed, there is still a very interesting part of the subject which must be left for another time; namely, the relation of fractional pitch windings to squirrel-cage motors.

THEORY

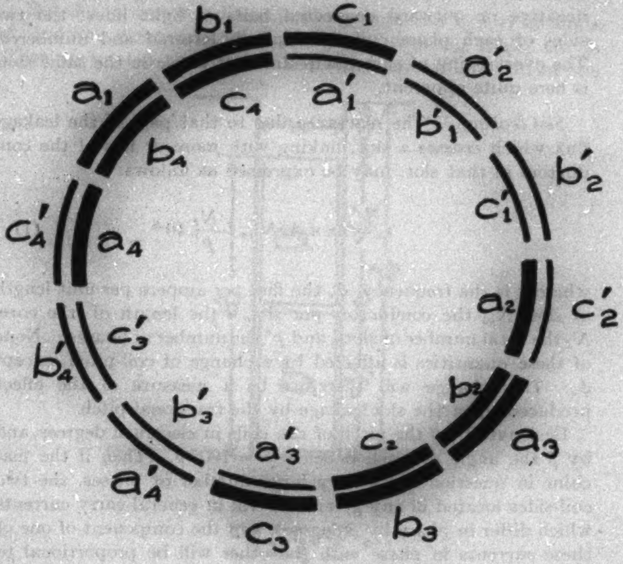
The theoretically ideal induction motor would have a very large number of symmetrically placed phase windings of full pitch on both primary and secondary structures, the primary windings being supplied with the same number of equal, symmetrical, simple harmonic electromotive forces. In this case the flux density across the air-gap, the primary current, and the secondary current would be distributed sinusoidally around the gap periphery at any instant, and these distributions would revolve smoothly around the periphery at synchronous velocity.

The chief difference between this ideal machine and the actual is that the number of phases in the latter is small and there must, therefore, be several adjacent conductors or slots carrying the same current at the same instant, thus forming what may be termed a *belt* of conductors in which the current increases and decreases as a unit. On either side of this belt is another, the current in which differs in phase from that in the first by a considerable angle, 60° in a three-phase and 90° in a two-phase motor. Thus the current varies from point to point around the periphery by jumps or steps rather than gradually, as in the ideal motor.

It is a well known fact which has been demonstrated both theoretically and experimentally that even an ordinary induction motor, if it have a low-resistance squirrel-cage secondary, and be supplied with simple harmonic electromotive forces, will have a gap flux whose peripheral distribution is approximately sinusoidal at each instant, the effect of the slot openings being neglected.

Even in the case of a phase-wound secondary, the most satisfactory common ground for calculation is the assumption of a sinusoidal peripheral flux distribution, for although it may be claimed that such a distribution does not exist in fact, the results of calculations based upon this assumption are sufficiently close to the observed facts to render its use quite warrantable.

Differential factor. When an harmonically distributed flux sweeps round the gap periphery it causes to be induced in the conductors of any given slot a simple harmonic electromotive force. If this slot is one of three per pole per phase of a three-phase motor, there will be induced in the conductors of these three slots of the same phase, three harmonic electromotive forces differing in phase by 20°, and these three electromotive forces will add together vectorially to form a resultant whose magnitude is about 0.96 of their numerical sum. This slight loss of effectiveness in electromotive force generation, which is due to the fact that different conductors of the same phase belt are at certain periods experiencing electromotive forces of opposite sign, may be termed *differential action*, since it consists in the differential cutting of flux by conductors of the same phase belt. Similarly the factor (0.96 in this case) by which the total numerical electromotive force must be multiplied to obtain the actual resultant electromotive force, may be called the *differential factor*. But differential action in these phase belts is not confined to electromotive force generation; it also appears in a similar manner in the production of an harmonically distributed magnetomotive force by currents in these belts. This means that a larger current per phase is required to produce a given magnetomotive force than in the ideal motor. If the secondary is supplied with an ordinary phase winding, the belts of this winding will be subject to the same differential action, both in the generation of electromotive force and in the production of torque by the reaction of the current belts on the gap flux. Moreover, in this latter case the overlapping of a secondary phase belt by parts of two primary phase belts, (or vice versa), results in local fluxes crossing the gap, which have components in phase with both primary and secondary currents and thus give rise to quadrature electromotive forces* which may be



Fig·1·

considered as another aspect of the belt effect or differential action.

The phenomena introduced by fractional pitch windings are largely of this same type, and may in most cases be treated as an

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*This subject has been treated by one of the writers under the head of *Belt leakage*. Proceedings International Electrical Congress, St. Louis, 1904, Vol. I, page 706.

extension of differential action. Thus if coils having a *pitch* or *throw* of less than 180° (electrical) be used for the winding of an induction motor, the effect will be to shift one of the layers of the winding around through a certain angle from its full pitch position, see Fig. 1, where a four-pole, three-phase winding with a two-thirds pitch is shown diagrammatically. The positive or backward connected belts are shown in heavy lines, and the negative or outward connected belts in light lines; the two sides of each phase coil are similarly lettered and numbered. The overlapping of currents of different phase in the same slots is here quite apparent.

Slot leakage. The reactance due to that part of the leakage flux which crosses a slot, linking with more or less of the conductors in that slot, may be expressed as follows:

$$x_s = 2\pi\, n\, \phi_s\, N^2_{cs}\, l \frac{N_t}{p'} 10^{-8} \qquad (1)$$

where n is the frequency, ϕ_s the flux per ampere per unit length of slot, N_{cs} the conductors per slot, l the length of the core, N_t the total number of slots, and p' the number of phases. None of these quantities is affected by a change of coil-pitch, except ϕ_s. This change will therefore be a measure of the effect produced upon the slot leakage by the fractional pitch.

Designate by θ the pitch of the coils in electrical degrees, and by β the angle of pitch deficiency = 180°-θ. Then if the machine in question has a very large number of phases, the two coil-sides located in any given slot will in general carry currents which differ in phase by β degrees, and the component of one of these currents in phase with the other will be proportional to cos β. If the product of the inductances of these two coil-sides is equal to the square of their mutual inductance, *i.e.* if there be no relative leakage flux between them, the ratio of the average leakage flux linked with one, to what it would be with full pitch winding and no phase difference between the two currents, is $\frac{1+\cos\beta}{2} = \cos^2\frac{\beta}{2} = \sin^2\frac{\theta}{2} = k_p$. This may be called the slot-pitch factor, under the two above mentioned conditions. But neither of these conditions exists in practice.

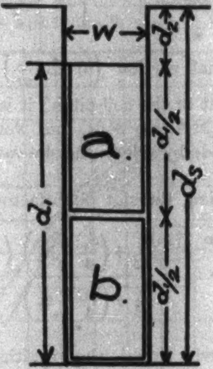
Consider first the relative leakage between the two coil-sides in the same slot. Referring to Fig. 2, the flux linked with coil b per inch length of slot for one ampere in b is

$$\phi_{bb} = \frac{3.2}{w}\left(\frac{d_1}{6} + \frac{d_1}{2} + d_2\right)$$

The flux linked with b per inch of slot for one ampere in a is

$$\phi_{ab} = \frac{3.2}{w}\left(\frac{d_1}{4} + d_2\right)$$

But the current in a differs in phase from that in b by an angle β, and the component of ϕ_{ab} in phase with ϕ_{bb} is $\phi_{ab}\cos\beta$. Then the total in-phase flux linked with b per slot inch and for one ampere distributed uniformly over the whole copper section of the slot, is,



Fig·2·

$$\phi_b = \frac{\phi_{bb} + \phi_{ab}\cos\beta}{2} = \frac{3.2}{w}\left[\left(\frac{d_1}{3} + \frac{d_2}{2}\right) + \cos\beta\left(\frac{d_1}{8} + \frac{d_2}{2}\right)\right]$$

Similarly

$$\phi_{aa} = \frac{3.2}{w}\left(\frac{d_1}{6} + d_2\right)$$

$$\phi_{ba} = \frac{3.2}{w}\left(\frac{d_1}{4} + d_2\right)$$

and $$\phi_a = \frac{\phi_{aa}+\phi_{ba}\cos\beta}{2} = \frac{3.2}{w}\left[\left(\frac{5}{24}d_1 + \frac{d_2}{2}\right)+\cos\beta\left(\frac{d_1}{8}+\frac{d_2}{2}\right)\right]$$

Then since each coil has one side in the bottom and the other in the top of a slot, the average flux linkage per ampere inch of slot will be

$$\phi_s = \frac{\phi_a+\phi_b}{2} = \frac{3.2}{w}\left[\frac{d_1}{12}+\left(\frac{d_1}{4}+d_2\right)\left(\frac{1+\cos\beta}{2}\right)\right] \qquad (2)$$

or $$\phi_s = .267\frac{d_1}{w}+\frac{3.2}{w}\left[\frac{d_1}{4}+d_2\right]\sin^2\frac{\theta}{2}.$$

There is thus a small portion $\left(0.267\frac{d_1}{w}\right)$ of the slot leakage which is independent of the coil-pitch; it is obviously that part which lies between the two coils, and would disappear if the latter were placed side by side in the slot rather than one on top of the other.

With this correction, the slot pitch-factor becomes

$$k_p = \frac{\frac{d_1}{12}+\left(\frac{d_1}{4}+d_2\right)\left(\frac{1+\cos\beta}{2}\right)}{\frac{d_1}{12}+\left(\frac{d_1}{4}+d_2\right)} \qquad (3)$$

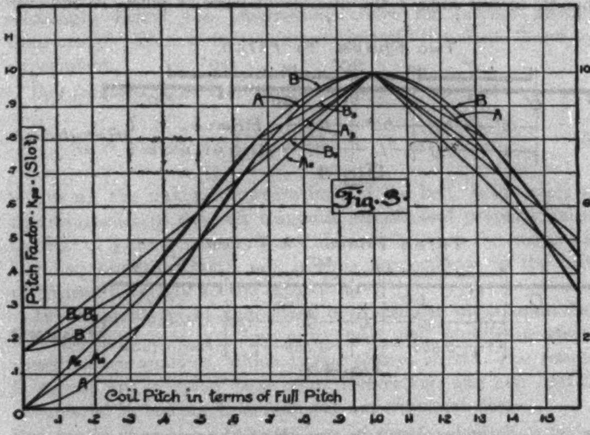
If the slot is partly closed, the resulting increase in ϕ_s is common to both coils and would involve a change in only that part of formula (2) which is affected by the coil-pitch.

In Fig. 3, curve *A* gives the values of $\frac{1+\cos\beta}{2}$ corresponding to different values of the coil-pitch, and curve *B* gives the corresponding values of k_p from equation (3), for a motor with open slots, in which the coils occupy about 80% of the slot depth. If the slots be partly or wholly closed, the constant part of equation (2) decreases relatively and the corresponding k_p curve will drop down, approaching more nearly to curve *A*.

In all this a very large number of phases has been assumed. Consider now the effect of a small number of phases. Take for example a two-phase motor with ¾ pitch. $\beta = 45°$ and k_p taken from curve *B*, Fig. 3, is 0.88. The two layers of the winding will be as in Fig. 4, where the relative phases of the currents in the several belts are indicated. Consider the 0° belt in the upper layer; half of it overlaps a 0° belt in the lower layer and the pitch-factor for this half is therefore 1; the other half overlaps a 90° belt in the lower layer, with a corresponding pitch-factor of 0.585. Thus the average pitch-factor for the belt is 0.792 in place of 0.88 as given by curve *B* or equation (3).

If the coil-pitch is deficient by one or more whole belts, the conditions will be exactly the same as those for which the curve *B* Fig. 3, was calculated. Therefore that curve will give the correct pitch-factor of a three-phase motor for a $\frac{1}{3}$ and for a $\frac{2}{3}$ pitch, and of a two-phase motor for a $\frac{1}{2}$ pitch winding.

A little consideration will show that between these points the actual pitch-factor will follow a straight-line law.



In Fig. 3 the lines B_2 and B_3 show the variation in k_p for two and three-phase motors respectively. A_2 and A_3 show the same factors when the relative leakage between the two coil-sides in the same slot is neglected.

Tooth-tip or "zigzag" leakage. The expression for the tooth-tip leakage reactance is of the same form as that for the slot leakage;

$$x_{tt} = 2\pi\, n\, \phi_{tt}\, N^2{}_{sc}\, l\, \frac{N_t}{p^1} 10^{-8} \qquad (4)$$

where ϕ_{tt} is the tooth-tip flux per ampere inch of slot, for both primary and secondary.

As far as the fractional pitch effect is concerned, this element is exactly on a par with that part of the slot leakage which crosses the slot above the conductors, since it is wholly common to both coil-sides. The *tooth-tip pitch-factor* will therefore be that shown by lines A_2 and A_3 Fig. 3.

Coil-end leakage. The coil-end reactance may be expressed as follows:

$$x_f = 2\pi\, n\, \phi_f\, p \left(\frac{N}{2p}\right)^2 l_c\, 10^{-8} = \frac{2\pi}{4}\, n\, \phi_f \frac{N^2}{p}\, l_c \qquad (5)$$

where ϕ_f is the flux per ampere inch of the whole phase belt bundle of coil ends, p the number of pairs of poles, N the conductors per phase and l_c the length of the two ends of one coil, usually about three times the coil-pitch. There are two terms in equation (5) which vary with the coil-pitch, l_c in a comparatively simple manner, and ϕ_f in a manner not so obvious.

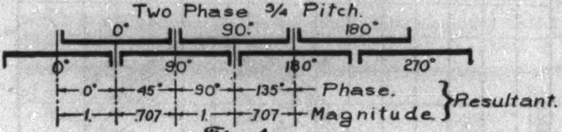

Two Phase 3/4 Pitch.
0°
90°
180°
0°
90°
180°
270°
0° 45° 90° 135° Phase.
1. .707 1. .707 Magnitude.
Resultant.

Fig. 4.

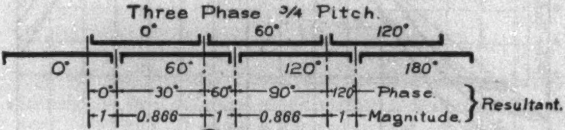

Three Phase 3/4 Pitch.
0°
60°
120°
0°
60°
120°
180°
0° 30° 60° 90° 120 Phase.
1 0.866 1 0.866 1 Magnitude.
Resultant.

Fig. 4a.

For a circular coil in air, ϕ_f, the flux linked with one inch of the coil as a whole, per ampere distributed uniformly throughout the section of the coil, is proportional to the logarithm of the ratio of coil diameter to the diagonal of its cross-section, provided this ratio is large. For coils such as are used on induction motors this relation holds only in a general way, especially when the mutual inductive effect of neighboring coils is taken account of, and when the pitch is fractional. However, within practical limits ϕ_f would increase in approximate logarithmic relation to the coil-pitch, were it not for the mutual inductive effect of adjacent phases, and the curve representing this relation would tend toward a zero which is not that of the pitch.

Consider now the mutual inductive effect of adjacent phases. For pitches less than unity, this decreases in about the same ratio as the self-inductive effect and thus does not much change the general shape of the curve. But for values of the pitch greater than unity, the mutual inductive effect of opposing phases begins to count and to reduce considerably the otherwise value of ϕ_f. Thus the curve showing the relation between ϕ_f and the coil-pitch should be logarithmic in its general character, tending toward zero at some small (not zero) pitch, and falling increasingly below the logarithmic curve for pitches greater than unity. This, in fact, is approximately the shape found by experiment.

Belt leakage. The belt reactance may be expressed:

$$x_b = 2\pi\, n\, \phi_b\, 2\, p \left(\frac{N}{2p}\right)^2 l\, 10^{-8} = \pi\, n\, \phi_b \frac{N^2}{p}\, l \qquad (6)$$

where ϕ_b, the flux per ampere inch of the belt, is inversely as the reluctance of the belt magnetic circuit, and proportional to the $\sin^2$ of $\frac{1}{2}$ the angle of phase difference between the currents in the two opposing belts. ϕ_b is thus proportional to the belt-pitch and inversely to the air-gap.*

In the analysis of the effect of fractional pitch upon belt leakage, each case is a law unto itself, and requires a special quantitative analysis, which is not always short. The results, however, are in some cases most interesting, and can best be considered in conjunction with the experimental data.

Exciting reactance. In the case of fractional pitch, a higher flux density is required in the gap in order to produce the same resultant electromotive force, because the electromotive forces in the two sides of any given coil differ in phase by β degrees. The electromotive force differential-factor is then $\cos\frac{\beta}{2}$ or $\sin\frac{\theta}{2}$ where θ is the coil-pitch angle.

Not only is the exciting current higher because of the increased gap density, but it is still further increased because of the overlapping of currents of differing phase and the consequent reduction in effectiveness for magnetomotive force production. The magnetomotive force differential factor is cos $\beta/2$ only when the coil-pitch is an exact multiple of the belt-pitch. For example, take the two-phase motor with 0.75 coil-pitch, Fig. 4, the average of the resultant currents is $\frac{1.707}{2} = 0.853$, but $\cos\frac{\beta}{2} = 0.96$. In Fig. 5, curve E shows the electromotive force differential-factor, M_3 the three-phase and M_2 the two-phase magnetomotive force differential-factor. The pitch-factor for the exciting reactance is then the product of E and M_2 or of E and M_3 and is shown in curves B_2 and B_3 of Fig. 6.

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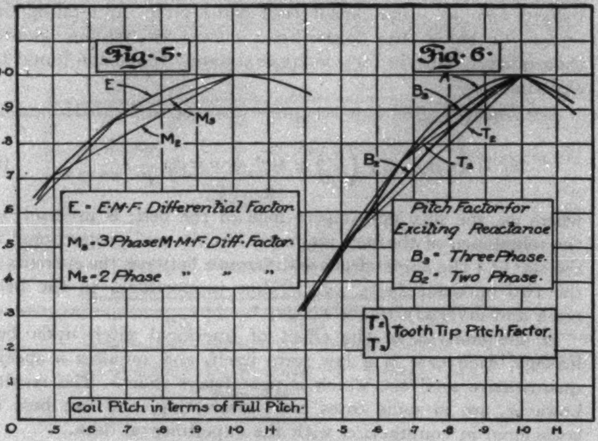
*See the paper referred to in note at bottom of third page of this paper.



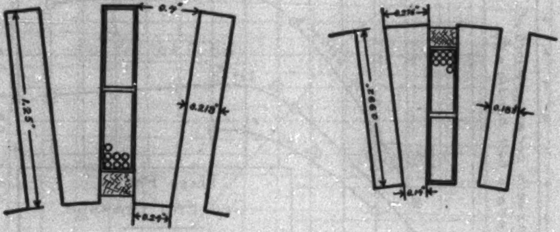
RESULTS OF EXPERIMENTS

The motor tested had 48 slots, (see Fig. 7) on stator and rotor and several sets of coils were used in the same core. Short-circuit tests were made at 300 and at 60 cycles, and open-circuit tests at 60 cycles. The latter were made with rotor stationary. Each set of coils had the same number of conductors per slot, as had the rotor and stator coils.

Coil-end reactance. The core was removed except for two plates, just sufficient to support a set of short coils. Short-circuit tests with this arrangement were practically useless owing to the relatively large exciting current; so the primary and secondary were connected in series, phase for phase, and the opposing belts set opposite each other. Then, since there were the same number of turns in primary and secondary, no flux crossed the gap, and the total impedance was accurately determined. Moreover, by measuring the drop across primary and secondary, the two impedances were separated. The very small slot reactance due to the two core discs was then computed and subtracted from the total, leaving the coil-end reactance alone.

Two sets of coils were employed in these tests. One set with a pitch of twelve slots was connected for three phases; two poles and four poles; half and full pitch respectively; both primary and secondary being connected in exactly the same manner

Fig. 7.



Stator—48 Slots

Rotor—48 Slots

The other set with a pitch of nine slots was connected for three phases; two poles, four poles, six poles, and eight poles; $\frac{3}{8}$ pitch, $\frac{3}{4}$ pitch, $1\frac{1}{8}$ pitch, and $1\frac{1}{2}$ pitch respectively; making in all six combinations with the short coils.

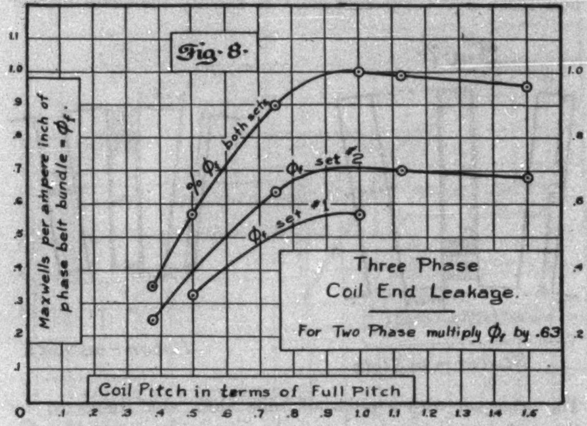
From the reactances obtained from these tests, the corresponding values of ϕ_f were computed by means of equation (5), in which l_c was taken as the total length for both primary and secondary. The results were plotted in the curves of Fig. 8. The difference between ϕ_f for the twelve-slot coils and the nine-slot coils is due to the fact that in the latter case the primary and secondary coil ends were bent farther back, thus leaving more room for leakage between them.

The upper curve of Fig. 8, shows both sets brought together by plotting each set in terms of its full pitch value. The curve of Fig. 9 shows the total coil-end pitch-factor for a special case where l_c is taken equal to 5 in. $+ 2.8\lambda_c$, λ_c being the coil-pitch in inches. The pole-pitch was taken as 10 in.

The coil-end pitch-factor is then:

$$k_{pc} = (\phi_f \text{ in terms of that for full pitch}) \times \frac{5+2.8\lambda_c}{5+2.8\,\lambda_p}$$

If all the coil-end leakage be charged to the primary, the corresponding full pitch value of ϕ_f for the first set of tests is 1.14, and 1.35 for the second set. The first of these corresponds more nearly to a normal induction motor.



For a squirrel-cage motor with bars extending well out from the core, the value of ϕ_f (all charged to primary) is known to be about one or a little more, which is very close to the value given above for a wound rotor. No experiments of this sort were made in the present investigation; but many instances are at hand where a considerable change has been made in the reactance of a squirrel-cage motor by altering the disposition of the end-rings. The writer hopes to investigate this matter in the not distant future.

Slot reactance. Following the above described coreless tests, the normal core of length $l = 3.2$ in. was replaced and tests were made with two different sets of coils; one set having a coil pitch of twelve slots and the other nine slots. The first set was connected in four combinations, two-phase two-poles; two-phase four-poles; three-phase two-poles; and three-phase four-poles; the second set was connected in five combinations, two-phase four-poles; three-phase, two-poles, four-poles, six-poles, and eight-poles. In the second set the wires were placed in the slots without taping and were depressed as much as possible, see Fig. 10.

Series tests were first made with the secondary belts directly opposite the corresponding primary belts, thus eliminating both tooth-tip and belt reactance.

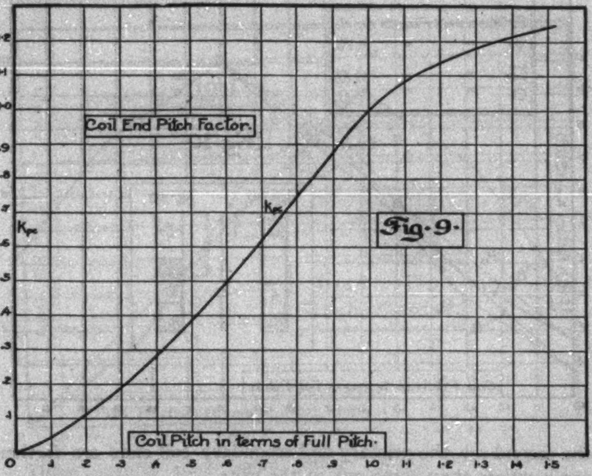


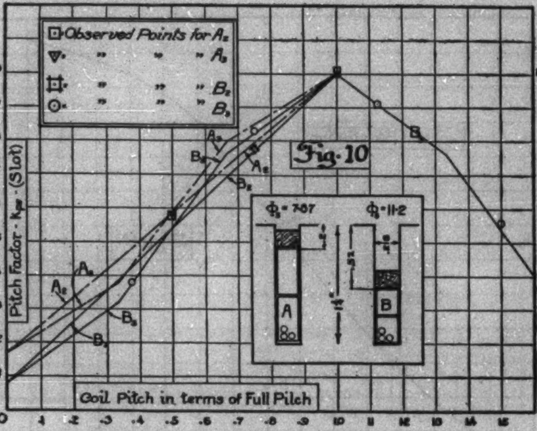
Fig. 9.

Ordinary short-circuit tests were then made, (*a*) with belt opposite belt as in the series test, (*b*), one half of the tooth-pitch beyond position "*a*", where the tooth-tip leakage is a maximum, and (*c*) one half belt beyond position "*a*" where the belt leakage is a maximum.

Tests were then made with the secondary open circuited to determine the exciting reactance.

The short-circuit tests "*a*" gave reactances uniformly two or three per cent. lower than the series tests, as was to be expected.

From the reactances obtained from the series tests, the coil-end reactances, (as calculated with the aid of the coreless tests) were then subtracted. The remainders are the slot reactances. The full pitch values of ϕ_f used in calculating x_f were 0.66 for the first set, (the twelve-slot pitch coils), and 0.70 for the second set, (the nine slot pitch coils). In both these cases, the coil-ends were bent well back in order to make room for the temporary between-coil connections which had to be changed several times. At first 0.70 was chosen for both sets, but it was found that 0.66 gave more consistent results for the slot leakage in the first set. This is also what might have been expected since, in the second set, the primary and secondary coil-ends are farther apart where they come out of the slots.



From the slot reactances obtained above, ϕ_s was calculated from equation (1). The slot pitch-factor is then $k_{ps} = \phi_s \div \phi_{s1}$ where ϕ_{s1} is the value of ϕ_s for full pitch.

The values of k_{ps} thus determined are plotted in Fig. 10 where the calculated curves from Fig. 3 are also shown. It will be noted that the deviations of the observed points from the calculated curves to which they belong, are within the reasonable errors of observation and calculation, particularly when it is remembered that owing to the comparatively large values of x_f, which were subtracted from the series test reactance x to get x_s the slot reactance, a moderate change in ϕ_f will shift the relative values of k_{ps} so that when plotted they appear to have little relation to the theoretical curves.

Tooth-tip or "zigzag" leakage. The difference between the "b" and the "a" reactances gives the maximum tooth-tip reactance x_{tt}, but it gives in addition a small portion of the belt reactance.

From this difference, ϕ_{tt} may be calculated by equation (4) and thence the tooth-tip pitch-factor. The results are plotted in Fig. 11, together with the theoretical curves A_2 and A_3 for two- and three-phase respectively, taken from Fig. 3.

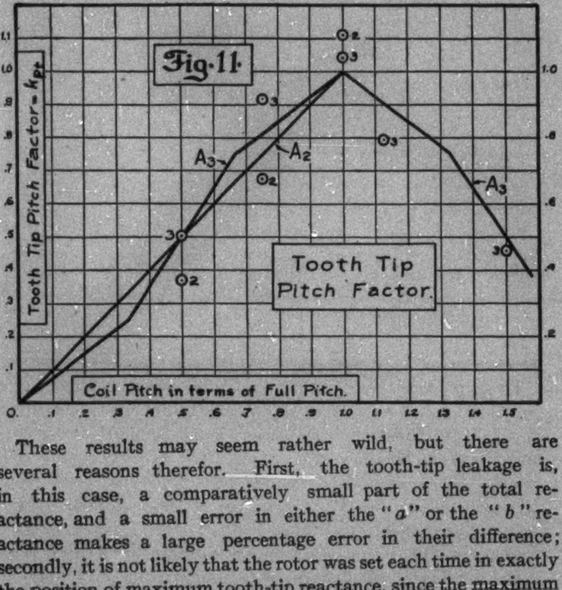


Fig. 11.

These results may seem rather wild, but there are several reasons therefor. First, the tooth-tip leakage is, in this case, a comparatively small part of the total reactance, and a small error in either the "a" or the "b" reactance makes a large percentage error in their difference; secondly, it is not likely that the rotor was set each time in exactly the position of maximum tooth-tip reactance, since the maximum is a narrow one owing to the open slots on both sides of the gap; thirdly, because of the inevitable presence of the uncertain and variable amount of belt leakage mentioned above. Taking these things into account, the results are in very fair accord with the theory. There is every reason to believe that this element of the leakage follows the theory outlined, quite as closely as does the slot leakage.

Belt leakage. The maximum belt reactance was obtained from the short-circuit tests by subtracting the "*a*" reactance from the "*c*" reactance. The experimental results are given in Table I, and a few typical cases will be considered. In column x_{B_3} the two-phase belt reactances are reduced to two-thirds of their actual values for comparison with the three-phase reactances.

TABLE I

			No.	Pitch.	x_B	x_{B_3}
12-slot pitch	2 phase	2 poles	1	0.5	11.32	7.52
		4 poles	2	1.	6.02	4.01
	3 phase	2 poles	3	0.5	1.38	1.38
		4 poles	4	1.	0.846	0.846
9-slot pitch	2 phase	4 poles	5	0.75	0.81	0.54
	3 phase	2 poles	6	0.375	0.535	0.535
		4 poles	7	0.75	0.24	0.24
		6 poles	8	1.125	......	......
		8 poles	9	1.5	0.175	0.175

First compare the two-phase and three-phase belt reactances; No. 1 and No. 3 are alike in all other respects, but the two-phase is nearly 5.5 times the three-phase value; similarly with No. 2 and No. 4. The theoretical ratio of two to three phase is 5.1 for the same number of slots per belt; when the above results are corrected on this latter score, they compare still more favorably with the theoretical ratio.

Compare No. 1 and No. 2, the only difference between which is the number of poles and the fractional pitch. In No. 1 ϕ_b* is twice as great because of the increased belt pitch and p is one half; therefore x_b should be four times as great were it not for the pitch-factor which is thus, 0.53, about the same as for the slots.

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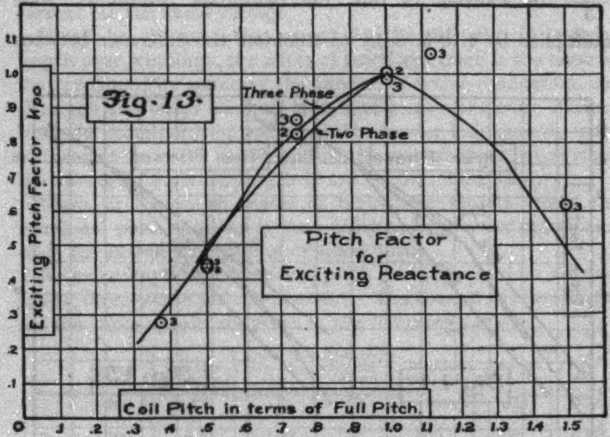
*See equation (6.)

Compare No. 2 with No. 5, the only difference being in the coil-pitch. The reason for the great reduction will appear from an inspection of Fig. 4, which represents the two layers of the ¾ pitch winding of No. 5. The effect of the overlapping of the two layers is to double the number of resultant belts and to decrease the phase difference between them to one-half. There is still an unbalancing of the magnetomotive forces due to the different magnitudes of the resultants, but this cannot be analyzed by means of equation (6).

Comparing No. 5 and No. 7, which differ only in phase, we find no such contrast as between No. 1 and No. 3. The reason for this will appear from the belt diagram of No. 7 shown in Fig. 4a; namely, that the maximum belt width is here reduced to only ⅔ of its original value, whereas in No. 5 it was reduced to one-half. In fact, the maximum belt width is the same in No. 5 and No. 7, although they are two and three-phase respectively.

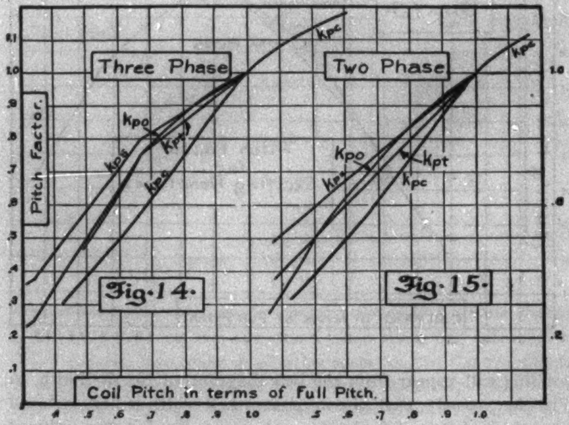


The result of this analysis is to show that the fractional pitch effect on belt leakage is largely dependent upon the relation between the coil-pitch deficiency and the belt-pitch, and that a proper choice of this relation makes a relatively very large reduction in the belt leakage, especially in a two-phase motor.

Such a choice also smoothes out the large kinks of the current distribution, and has much the effect of doubling the number of phases.

Exciting reactance. The exciting reactance was determined from the open-circuit tests made with rotor standing in the position of maximum reactance, namely, with the rotor teeth opposite the stator teeth.

In order to make the results comparable and thus be able to determine the pitch-factor, the exciting reactances were all reduced to a three-phase two-pole basis by multiplying by $\frac{p' p^2}{3}$. In addition to this, the two-phase reactances were multiplied by 1.10 in order to eliminate the difference between the differential-factors of the two and the three-phase motors at full pitch.



In Fig. 13, the observed values of the pitch-factor for the exciting reactance are plotted together with the theoretical curves. No satisfactory explanation has been offered for the considerable deviation of the two high points on the right of the figure.

SUMMARY

All the principal pitch-factor curves for the three-phase motor are assembled in Fig. 14, and those for the two-phase motor in Fig. 15.

To sum up, the effects of a fractional pitch winding are:

a. A reduction of the several components of the leakage reactance.

b. A reduction of over-all length of the motor.

c. In some cases, a considerable gain in the convenience of winding as well as a saving of space.

d. A decrease in the exciting reactance; that is, higher densities in all parts of the magnetic circuit and a higher exciting current for the same voltage.

It will be observed that except for the reduction in endwise length over windings, the effect of fractional pitch is the same as that produced by reducing the number of active conductors, but although the latter method is in many cases the more efficient from the standpoint of operation, the former is frequently more convenient from the standpoint of the manufacturer, even when the saving in endwise length is not a controlling factor.

There are, however, cases of high-speed motors where the fractional pitch winding is more efficient from every standpoint than the full pitch winding of fewer turns.

As an example of a fractional-pitch problem, consider a three-speed, three-phase induction motor. The comparative constants for the three speeds are given in the following table:

Poles.	rev. per min.	Relative gap density	Relative core density.	Relative exciting current.	Relative reactance.	Relative safe output	Power-factor
4	1800	0.77	115	59	95	103	0.93
6	1200	100	100	100	100	100	0.90
8	900	154	115	237	75	84	0.76

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907.

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ZIGZAG LEAKAGE OF INDUCTION MOTORS

BY R. E. HELLMUND

Various formulas have been given heretofore for the predetermination of the leakage coefficient of induction motors, but the results derived from these formulas are so divergent that the formulas themselves are rather discredited. It seems to the writer that the following study about the values of the zigzag leakage may help to clear this somewhat unsettled question.

In the study of induction motors the leakage coefficient is one of the most important factors, and therefore this value will be chiefly discussed in what follows. Unfortunately the definition of this value is very unsettled in practice. Some writers when deriving the induction motor theory introduce the leakage coefficient as a ratio of magnetic reluctances in the motor, and others introduce it as a ratio of fluxes which exists while no secondary reactance takes place. These two different definitions may be represented by the two following equations:

$$\frac{R_s}{R_p} = \tau_1 \tag{1}$$

where R_s = the reluctance of the flux being interlinked with the secondary windings, R_p = the reluctance of the flux being interlinked with the primary winding, and τ_1 = the primary leakage coefficient.

$$\frac{F_p}{F_s} = \tau_2 \tag{2}$$

where F_p = the flux being interlinked with the primary winding, F_s = the flux being interlinked with the secondary winding, and τ_2 = the primary leakage coefficient.

Two other definitions which are frequently used are as follows:

$$\frac{R_p}{R_e} = \tau_3 \tag{3}$$

where R_p is again equal to the reluctance of the total flux interlinked with the primary winding, R_e = the reluctance of that part of the flux which is interlinked with the primary winding but not with the secondary winding, and τ_3 = the primary leakage coefficient.

$$\frac{F_e}{F_p} = \tau_4 \tag{4}$$

where F_p = the total flux interlinked with the primary winding, F_e = that part of the flux which is interlinked with the primary winding but not with the secondary winding, and τ_4 = the primary leakage coefficient.

Since

$$F_p = F_s + F_e$$

we may easily find

$$\tau_2 = \frac{1}{1-\tau_4}$$

Similarly, a relation between τ_1 and τ_3 may be established.

It is, therefore, always possible to find the values τ_1 and τ_2 if τ_3 and τ_4 are known, so it will be sufficient to deal in the following with the two latter values only. For instance, a three-phase motor with one slot per pole per phase in both members has been chosen. Fig. 1 shows the arrangements of the slots and windings, and the rotor in such position that the stator and rotor teeth do not coincide. It is simple to trace all the possible paths of the magnetic fluxes as shown by dotted lines. Moreover, in order to find the values of all the existing fluxes, it is simplest to treat the magnetic circuits as electric circuits. Fig. 2 gives the magnetic circuits reproduced from Fig. 1 as electric circuits. In all places where a flux passes through air a resistance has been introduced, while the practically very small reluctance of the magnetic paths in the iron has been neglected. The magnetomotive force which the primary magnetizing current impresses upon the primary teeth has been replaced by electromotive forces, E_1, E_2, and E_3. It can be easily shown that the magnetomotive forces in opposite teeth must be equal in value and in direction, and therefore that all current fluxes in directly opposite parts of the system must correspondingly be equal in value and opposite in direction. This has been taken into account in numbering the circuits and in assuming the current direction as indicated by arrows.

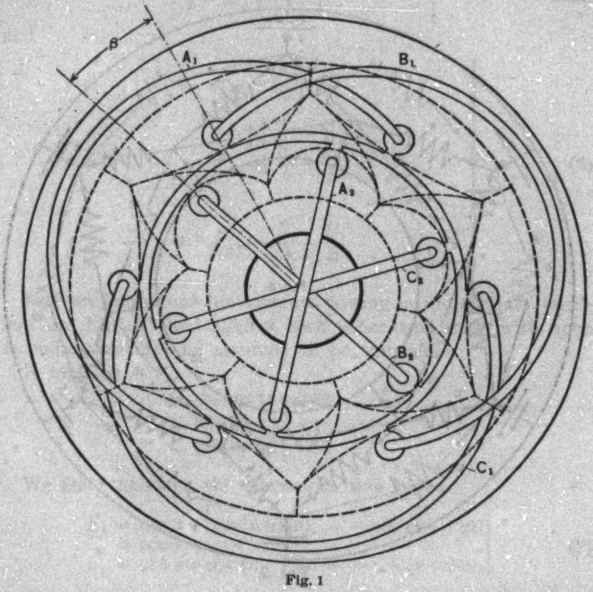
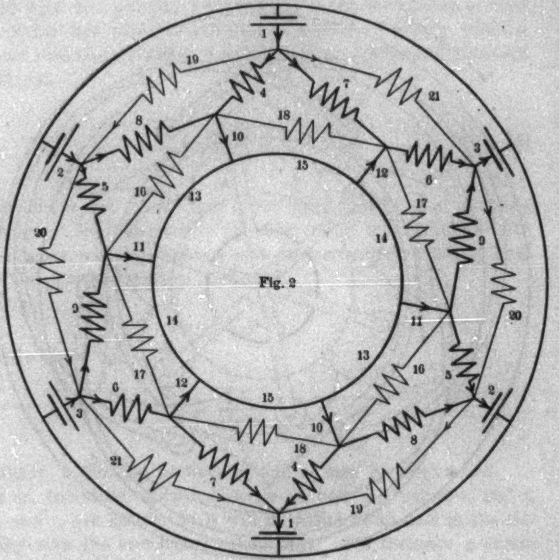


Fig. 1

It would now be possible to find all the values of the various fluxes and then to determine the value of the zigzag and slot leakage together. The zigzag leakage alone may be found simply by omitting the slot leakage fluxes in the further calculation, although thereby a small error in the values of the primary fluxes is introduced the same are of no practical importance at all, the slot leakage being mostly less than 1% of the total primary field. It is obvious from the figures that the resistances of the circuit 4, 5, and 6 are equal, and that also the resistances of the circuits 8 and 9 are equal. If, therefore, we put

$$r_4 = r_5 = r_6 = b$$
$$r_7 = r_8 = r_9 = a$$

and



1
19
4
7
21
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18
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3
2
15
12
6
5
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17
20
14
9
11
Fig. 2
9
11
20
14
13
16
5
17
12
6
15
2
3
10
18
8
21
4
7
19
1

FIG. 2

we find from Fig. 2

$$E_1 - F_4 b + F_8 a - E_2 = 0$$
$$E_2 - F_5 b + F_9 a - E_3 = 0$$
$$E_3 - F_6 b + F_7 a - E_1 = 0$$

and

$$F_4 b - F_7 a = 0$$
$$F_5 b - F_8 a = 0$$
$$F_6 b - F_9 a = 0$$

From this we find

$$\left.\begin{aligned} F_1 &= E_1\left(\frac{1}{a}+\frac{1}{b}\right) \\ F_2 &= E_2\left(\frac{1}{a}+\frac{1}{b}\right) \\ F_3 &= E_3\left(\frac{1}{a}+\frac{1}{b}\right) \end{aligned}\right| \tag{5}$$

and

$$\left.\begin{aligned} F_{10} &= \frac{E_1}{b}+\frac{E_2}{a} \\ F_{11} &= \frac{E_2}{b}+\frac{E_3}{a} \\ F_{12} &= \frac{E_3}{b}-\frac{E_1}{a} \end{aligned}\right| \tag{6}$$

Now we know that the currents flowing in the primary windings are 120°, shifted against each other, and may, with open secondary circuits, be assumed to be sinusoidal.

It may be

$$\begin{aligned} i_{b_1} &\equiv \cos(x+240) \\ i_{a_1} &\equiv \cos x \\ i_{c_1} &\equiv \cos(x+120) \end{aligned}$$

We find, therefore, the magnetomotive forces

$$\left.\begin{aligned} E_1 &= \cos x+\cos(x+240) = -\cos(x+120) \\ E_2 &= \cos x \\ E_3 &= \cos x+\cos(x+120) = -\cos(x+240) \end{aligned}\right| \tag{7}$$

It follows now from 5 and 7

$$\left.\begin{aligned} F_1 &= -\cos(x+120)\left(\frac{1}{a}+\frac{1}{b}\right) \\ F_2 &= \cos x\left(\frac{1}{a}+\frac{1}{b}\right) \\ F_3 &= -\cos(x+240)\left(\frac{1}{a}+\frac{1}{b}\right) \end{aligned}\right| \tag{8}$$

and from 6 and 7

$$\left.\begin{aligned}F_{10} &= -\frac{\cos(x+120)}{b}+\frac{\cos x}{a}\\ F_{11} &= \frac{\cos x}{b}-\frac{\cos(x+240)}{a}\\ F_{12} &= -\frac{\cos(x+240)}{b}+\frac{\cos(x+120)}{a}\end{aligned}\right| \quad (9)$$

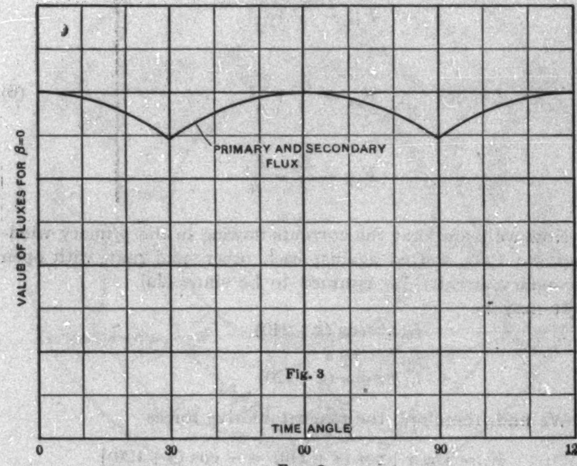

Fig. 3

It is now obvious that after the values a and b have been determined from Fig. 1 for a certain rotor position, the primary flux may be found for any time-angle, x, by simply adding arithmetically the values being found for F_1, F_2, and F_3 for this time-angle; in the same way the secondary flux may be found by adding the values of F_{10}, F_{11}, and F_{12}.

In Fig. 3 the primary and secondary flux as found in this way have been given as a function of the time for the rotor position for which the angle β, Fig. 1, is 0.

As will be seen, both fluxes change with the time,* but primary and secondary fluxes are always equal; this means that for this rotor position no zigzag leakage flux exists, and the leakage coefficient $\tau_4 = 0$.

In Fig. 4 the primary and secondary fluxes are given for a rotor position for which $\beta = 15°$; that is, for a position where the rotor slots are shifted about one-quarter tooth against the stator slots. It will be seen that both fluxes change again with the time, but their values are now different from each other. It is obvious that at any moment the difference between the primary and secondary fluxes represent the leakage flux. Fig. 5 gives the value of τ_4 as a function of the time as found from Fig. 4. The maximum value of τ_4 is for this rotor position about 0.177, and the average value may be found to be about 0.097.

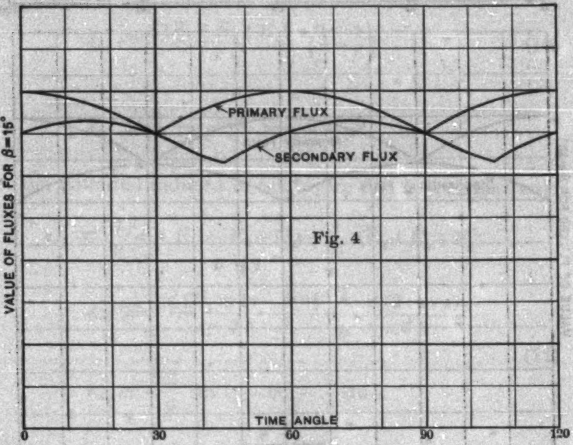

FIG. 4

Figs. 6 and 7 give the same curves as Figs. 4 and 5, but for a rotor position for which $\beta = 30°$; that is, for a position where the rotor slots are shifted about one-half tooth against the stator slots.

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* See study about the rotating field, *Electrical Review*, September 22, 1906.

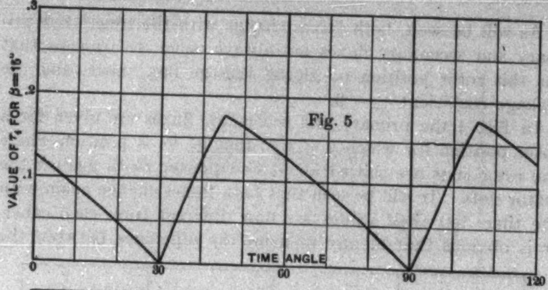

Fig. 5

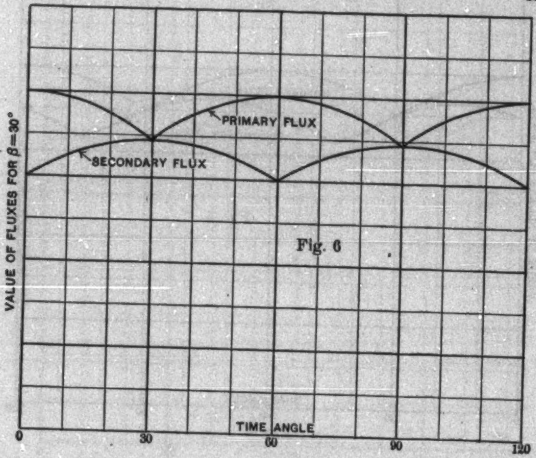

Fig. 6

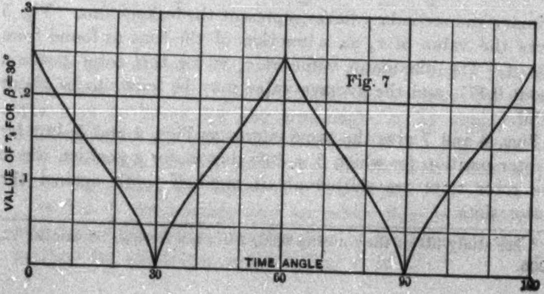

Fig. 7

In this case the maximum value of $\tau_4 = 0.25$, while the average value may be found to be about $\tau_4 = 0.134$.

It remains now to find what influence the magnetic leakage as found before has upon the value of the potentials being induced in the secondary circuits.

The potential induced in coil A_1 will be

$$e_{a1} \equiv \frac{d\,(F_1+F_2+F_3)}{d\,x}$$

or

$$e_{a1} \equiv \frac{d\,(E_1+E_2+E_3)}{d\,x}\left(\frac{1}{a}+\frac{1}{b}\right) \tag{10}$$

or

$$e_{a1} \equiv \frac{d\,(2\cos x)}{d\,x} = -\,2\sin x$$

For the potential induced in coil A_2 we find in a similar way,

$$e_{a2} \equiv \frac{1}{a}\,(-\,E_1 + E_2+E_3) + \frac{1}{b}\,(E_1+E_2+E_3)$$

or

$$e_{a2} \equiv \frac{1}{a}\,\frac{d\,[2\cos\,(x-60)]}{d\,x} + \frac{1}{b}\,\frac{d\,(2\cos x)}{d\,x}$$

$$e_{a2} \equiv -\frac{2}{a}\,\sin\,(x-60) - \frac{2}{b}\sin x \tag{11}$$

It is now simple to find the maximum value of the potential in coil A_1,

$$e_{a1}\ \text{max.} \equiv 2$$

and the effective potential in coil A_1

$$e_{a1}\ \text{eff.} \equiv \frac{2}{\sqrt{2}} \tag{12}$$

The maximum value of the potential in coil A_2 is obtained for

$$\frac{2}{a}\cos\,(x-60) \equiv -\frac{2}{b}\cos x \tag{13}$$

It is now possible to find for any ratio of *a* to *b*; that is, for any rotor position from 13 the value of *x* for which the secondary potential reaches its maximum, e_{a_2} maximum. Curve *A* in Fig. 8 gives the relation between the rotor position and the time-angle *x*, for which the secondary potential reaches the maximum value. After this curve has been determined, it is possible to find from 11 the maximum and the effective potential induced in the secondary winding. Curve *C* gives the secondary potential as found for different rotor positions. Curve *B* gives the primary potential as found from 12; the same is, of course, independent of the rotor position, on the assumption that the air-gap is uniform and that the influence of the slot

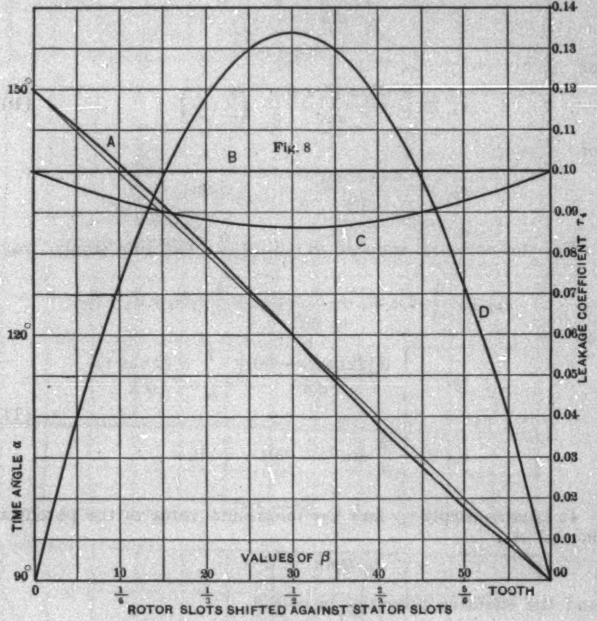

FIG. 8

openings may be neglected. Curve *D* represents the following value:

$$y \equiv \frac{e_{a_1}\,\text{eff} - e_{a_2}\,\text{eff}}{e_{a_1}\,\text{eff}}$$

where the value of e_{a_1} effective and e_{a_2} effective are taken from curves *B* and *C*.

A comparison of the average values for τ_4 as found from Figs. 3 to 7, with the values of y for the same rotor positions, shows that

$$\tau_4 \equiv y$$

This shows for the case under consideration the correctness of the partly customary method for determining the leakage coefficient τ_4 from tests, which consists in testing the primary and secondary potential of a motor and in assuming,

$$\tau_4 = \frac{e_{a_1}\,\text{eff} - e_{a_2}\,\text{eff}}{e_{a_1}\,\text{eff}} = \frac{F\,e}{F\,p}$$

As the average value for τ_4 we find from curve *D*,

$$\tau_4 \text{ average} \equiv 0.081.$$

The fact that curve *D* is not a straight line shows that it is not admissible to assume the leakage coefficient equal to the average of its maximum value and its minimum value, as has been done by various authors. The mistake which would thereby be introduced in the case under consideration is quite considerable. The average of the maximum value of τ_4 and its minimum is

$$\frac{0+0.134}{2} = 0.067;$$

that is, about 20% different from the real average value 0.081.

Fig. 9 shows the rotor in its position for $\beta = 30°$. A glance on this figure shows that τ_3 according to its previously given definition is $0.333 = \frac{1}{3}$, since the total primary flux of course passes through three teeth, while the leakage flux passes through $(2\times\frac{1}{2})$ tooth only. The ratio of the resistances of the two paths is therefore

$$\tau_3 = \frac{\frac{1}{3}}{2\times\frac{1}{2}} = \frac{1}{3}$$

The value of τ_4 for the same position was 0.134, and we see therefore that τ_4 and τ_3 are two entirely different values; in the case under consideration their difference amounts to more than 100%. This shows that it is of the highest importance in any study of the induction motor to make a strict distinction between the two values.

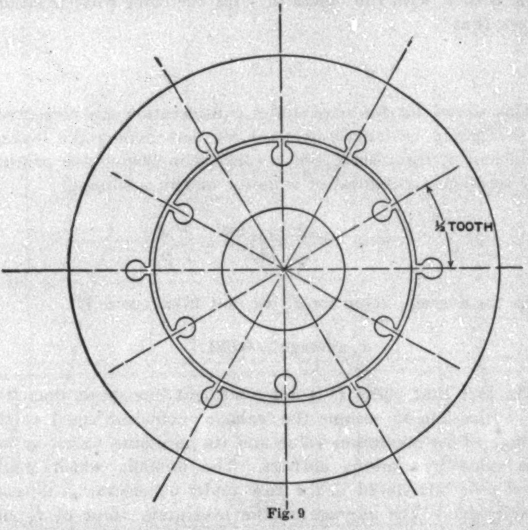

Fig. 9

The explanation of the phenomena causing the difference between τ_3 and τ_4 is comparatively simple. It is obvious that if the magnetomotive force and therefore the density over one pole face should be uniform, the values τ_3 and τ_4 would be equal. Since, however, the magnetomotive forces, and therefore the densities near the pole limits, are considerably smaller than near the center of the pole, it is obvious that the flux near the pole limits which forms that part of the flux which does not thread the secondary windings (*i.e.*, the leakage flux) must be much smaller than it would be in case of a uniformly distributed field.

It seems to the writer that in deriving the diagram of the induction motor the value τ_4 should be used, since for the field diagram the actual ratio of the various fields and not the reluctance of their paths is of interest. To introduce the value of τ_3 as leakage coefficient, as has been done by Heyland, Behn-Eschenburg, and others, is not correct unless another coefficient giving some ratio between the magnetomotive force of the main field and that of the leakage fields be introduced. The previous considerations apply, of course, to the zigzag leakage only, but it is obvious that similar facts apply to the other kinds of leakages.

The previous considerations were dealing with the leakage coefficient as determined on the assumption that no secondary reaction takes place. The coefficient τ_4 as previously determined would be the right value upon which the theories for the load conditions might be based, if the secondary reaction would be caused by sinusoidal secondary currents only for all load conditions. For the blocked rotor condition of the motor, that is, for the starting condition, this condition is fulfilled. Assuming that sinusoidal electromotive forces are impressed upon the motor we have found that all the fluxes in the motor are sinusoidal functions of the time, we also have found that the electromotive forces induced in the secondary circuits are sinusoidal. If, therefore, the secondary circuits are closed, the currents flowing will be sinusoidal and the reactions caused by secondary currents will be sinusoidal functions of the time

For all other load conditions the phenomena are not quite as simple. If the field set up by the primary windings had a sinusoidal space distribution over the poles, and if it were constant in value, and if it rotated with uniform speed, then all potentials induced in the secondary and, therefore, the currents in the secondary and the magnetic reactions, would be always sinusoidal, no matter what the speed of rotation of the rotor. This is, however, not the case. The curves given in Figs. 3, 5, and 7, for the total value of the primary field show that the latter varies in its strength.

We also may conclude from the previous considerations that the field does not rotate with uniform speed. If the field rotated with uniform speed, curve *A* of Fig. 8 would have to be a straight line. The speed of the field as a function of the time may be easily found from Fig. 8, curve *A*, and is shown by curve *A* in Fig. 10.

It also may be shown that not only the speed of the field as a whole varies, but that the speeds of the various parts of the field are different from each other, and vary with the time. If, therefore, the rotor rotates with a certain speed, the electromotive forces induced in the rotor windings are not only due to the slip, but there are also certain electromotive forces induced by the fluctuations of the strength of the primary field and by the irregularities in the speed of rotation of said field. (There is, of course, a possibility that the irregularities of the strength of the field and those of the speed of the field eliminate each other in their effect upon the secondary windings; it may be shown, however, that this is not the case.)

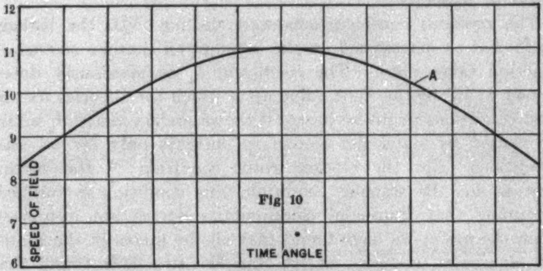

FIG. 10

It seems almost impossible to determine the exact phenomena for all load conditions. It is possible, however, to find pretty exactly what happens while the motor is running under no load. It can be shown that, while the rotor is running synchronously with a uniform speed the secondary reaction will cause the field distribution over the pole faces to have a step-form of such a shape that the area of each step is equal to the corresponding area of a sine wave. (See Fig. 11.)

The above causes of the secondary reaction have been partly discussed by other writers. A detailed and pretty complete account of them as well as a derivation of the field shape for the no load condition have been given by the writer in a study given in the *Electrical Review*, September 22, 1906.

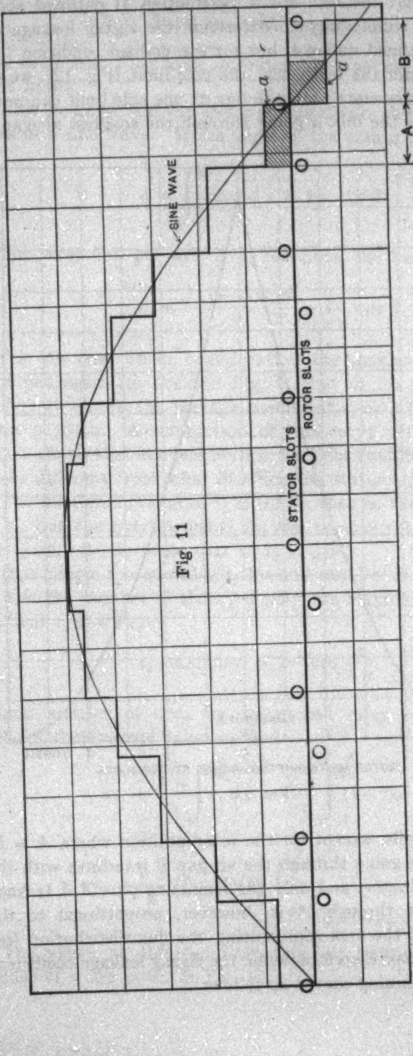
SINE WAVE
STATOR SLOTS
ROTOR SLOTS
a
a

Fig. 11

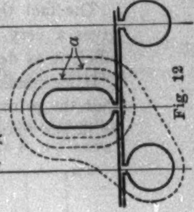

Fig. 12

The fact that the field has a distribution as outlined above gives a very simple way to determine the zigzag leakage coefficient as defined under 4, but for the no-load condition.

If we consider the teeth near the pole limit (Fig. 12), we see that the primary zigzag leakage flux at one pole limit can never be larger than the flux *a* going through the smallest air-gap *A* to the rotor, while, except for the rotor position where $A = B$, part of the flux going through the air-gap *B* interlinks with the secondary conductors and only the remaining part *A* is leakage flux The flux through *A* is, however, proportional to the smallest step of the area representing the flux distribution (see Fig. 11). We may therefore define the zigzag leakage coefficient for the light running motor as follows:

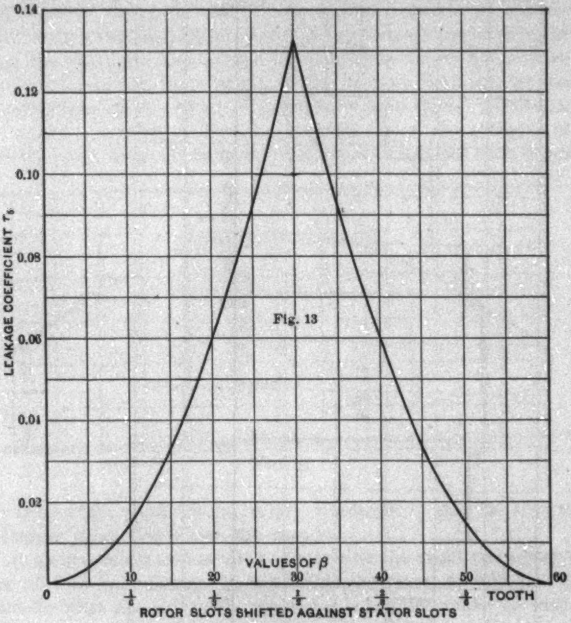

FIG. 13

$$\tau_5 = \frac{2 \times \text{area of smallest step}}{\text{Total flux area per pole}}$$

The coefficient 2 has to be introduced because each pole has two pole limits.

Now we know that the area a equals always the corresponding area of a sine wave. If the angle of the area a is β, we have

$$a = \int_0^\beta \sin x \, d x = 1 - \cos \beta$$

The total flux per pole is 2, therefore, the leakage is

$$\tau_5 = \frac{2\,(1 - \cos \beta)}{2} = 1 - \cos \beta$$

For the case under consideration the maximum leakage is obtained again for position Fig. 9, that is, for $\beta = 30°$.

Fig. 13 shows the leakage coefficient τ_5 as a function of the rotor position. A comparison of this curve with curve D of Fig. 8 shows that the leakage for the light running motor is entirely different from what it is for the stationary rotor.

The maximum value of τ_5 is 0.134; that is, the same as that of τ_4, but the average value for the various rotor positions is for τ_5 only 0.046, while that of τ_4 is 0.081.

It is simple to determine τ_5 for any number of slots per pole. If n is the number of slots per pole, the maximum leakage coefficient τ_5 is always:

$$\tau_5 \text{ maximum} = 1 - \cos \frac{\pi}{2\,n}$$

(equal number of slots for stator and rotor being assumed) and for the average value we find

$$\tau_5 \text{ av.} = \frac{2\,n}{\pi} \int_0^{\frac{\pi}{2n}} \tau_5 \, d\beta = \frac{2\,n}{\pi} \int_0^{\frac{\pi}{2n}} (1 - \cos \beta)\, d\beta$$

$$\tau_5 \text{ av.} = \frac{2\,n}{\pi} (\beta - \sin \beta) \Big|_0^{\frac{\pi}{2n}} = \underline{\underline{1 - \frac{2\,n}{\pi} \sin \frac{\pi}{2\,n}}}$$

The values as obtained from this last formula for different values of n are given in Fig. 14.

The fact that the leakage coefficient varies with the load condition makes it rather difficult to obtain an exact value for the various conditions between the no-load and blocked-rotor conditions. The writer has shown, in an article published in the *Electrical World*, that the secondary reaction of the light running motor does change not only the field distribution but also the wave shape of the no-load magnetizing current. It

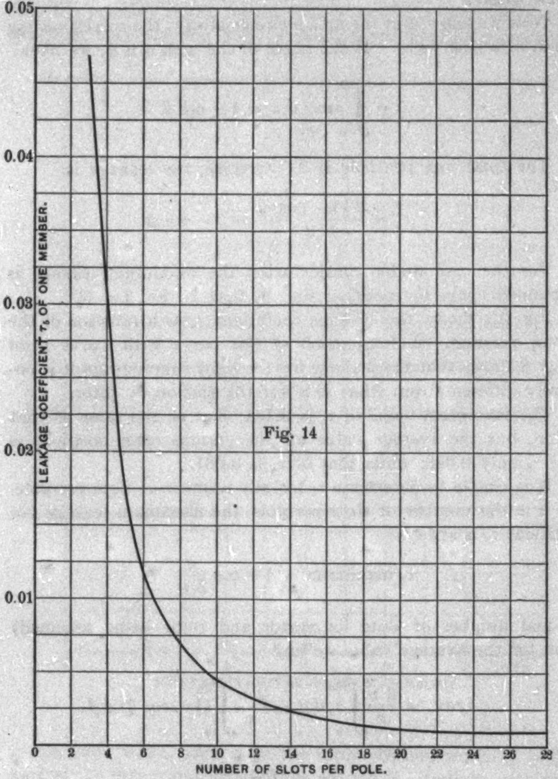

Fig. 14

remains to be investigated how the load currents combining with the magnetizing currents for the running motor are in their general character, wave shape, etc., before any final conclusions can be made. It seems reasonable, however, to assume that the right value for the leakage coefficient for the load conditions will be somewhere between τ_4 and τ_5. In fact, the writer observed quite frequently that the currents for low loads have a better power-factor than found from the diagram which is derived from the blocked-rotor condition. Of course it is necessary to be very careful in concluding from tests, since the change of the leakage coefficient, caused by the fact that the reluctance of the iron is not constant, may influence the results considerably. The writer has shown in an article in the *Electrical Review*, Jan. 29, '07, that the change of the leakage coefficient caused by the changing reluctance of the iron may amount to as much as 50% between no-load and blocked-rotor condition in commercial motors. Since these changes tend, however, to change the leakage so as to decrease it when the motor decreases in speed, the tests showing a power-factor for low loads, which is better than derived from the blocked-rotor test, seem to confirm the above theories.

It may appear that the previous considerations being of a rather theoretical nature will be of little practical value, since no final formula for the zigzag leakage for the various load conditions has been given. The more surprising it will be if the writer states that this paper is the result of an attempt to give an exact and practical formula for the calculation of the leakage coefficient. This paper should, therefore, be considered more as a preliminary work, which is merely intended to bring out certain facts which must be considered in connection with any study about the leakage coefficient.

It is obvious that in constructing a practical formula for the leakage coefficient it will be necessary on account of the rather complicated nature of the real phenomena to admit certain inexactnesses into the formula. Since this is the case it might seem advisable to use one of the existing formulas, as for instance, the one known as the Behrend formula. Although this latter formula gives for motors of standard design fairly exact values, the same seems to be to the writer objectionable for two reasons. A change of the slot dimensions will, for instance, according to this formula, change the value of the leakage considerably, while, in motors with a large number of slots per pole, a change of the slot dimensions does not affect the leakage very much. On the other hand, a change of the ratio of the pole-pitch to the width of core will, according to the formula, affect the leakage also considerably; while, in a motor with a small number of slots per pole, said ratio has little influence on the total amount of the leakage.

Since the various kinds of leakage are not dependent upon each other, a formula for the leakage should take them into consideration separately. A formula of this kind is the latest formula given by Behn-Eschenburg. This formula, however, gives, as mentioned before, the zigzag leakage coefficient as defined by formula 3 and the values for the zigzag leakage are, therefore, considerably too large. Moreover, the dimensions of the slot are not taken into consideration at all, and the so-called belt leakage discovered by Professor Adams* is also neglected. In spite of this, the latest Behn-Eschenburg formula gives also fairly exact values for the total leakage coefficient for standard motors, and the formula is fairly simple.

During several years of designing practice, the writer has become more and more convinced that the simplest formula is not at all the most practical one. In order to obtain a well-designed machine in which the best results are obtained from a certain amount of material, it is absolutely necessary for the designer to have formulas which not only give a fairly exact total result, but which also indicate in a fairly exact way the results of any change made in the design. If, for instance, the change of the slot dimensions has a noticeable influence on the performance of the motor, the designer should be able to know how much this influence amounts to. On the other hand, it seems to the writer perfectly indifferent whether the designer requires one minute or five minutes to determine the leakage coefficient of an induction motor while he is laying out a new line of machines, as long as even a small advantage may be obtained by spending five minutes instead of one. For routine design work, which, of course, should be done as quickly as possible, formulas are used very little, because most factors are usually known from previous tests.

*** The writer does not want to fail to call attention to the very valuable work about the determination of the induction motor leakage, done by Professor Adams. This paper is published in the *Transactions* of the International Congress of St. Louis.**

DISCUSSION ON "FRACTIONAL PITCH WINDINGS FOR INDUCTION MOTORS", AND "ZIGZAG LEAKAGE OF INDUCTION MOTORS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907.

J. C. Lincoln: Have experiments been made to determine the relative importance of the three kinds of leakage found in induction motors?

1. The leakage across the slots.
2. The leakage across the gap, or so-called zigzag leakage.
3. Leakage in the end-connections of the stator winding.

Have experiments been made to determine the relative importance at full-load of these three sorts of leakages with reference to the main or useful flux?

Chas. P. Steinmetz: I want to call attention to one point that Professor Adams did not touch on, and that is with fractional pitch windings the extra insulation necessary plays an important factor in the design of both the motor and the alternating-current generator. That is, if we assume a Y-connected machine, three-phase, and use a fractional pitch we have increased insulation necessary on the end-windings where the opposite phases come together in the same slots. This has quite an effect on the design. I think that the vast majority of the motors we are building to-day of the induction type are built with fractional pitch windings as are also most of the alternators.

B. T. McCormick: I ask whether the claim for extra insulation is on the end-connectors or in the slots?

Chas. P. Steinmetz: The insulation is progressive; that is, if we start from the neutral point as we go out from the neutral point the extra insulation is necessary, because we have the full potential between phases instead of the potential from the winding to the neutral point.

Comfort A. Adams: Referring to the effect of fractional pitch upon the exciting current—I should like to point out that not only is the electromotive force induced in a fractional pitch winding by a given flux, less than that of a full-pitch winding, but the magnetomotive force and the flux produced by a given current with fractional pitch is less than that for full pitch. In other words, fractional pitch introduces differential action both in the electromotive force and in the magnetomotive-force generation. The two differential factors are fully treated in my paper.

It was stated by one of the speakers that if the magnetizing current increased in the same proportion as the reactance decreased, there would be no resulting gain in power-factor. That there is in some cases a very decided gain will be apparent when it is remembered that these two elements vary approximately in reciprocal relation. Take, for example, a motor in which the exciting current is 14% of the load current and the reactance electromotive force 30% of the induced electromotive force; assume that the pitch of the winding is reduced in such a way that the exciting current is increased one- and a-half times its original value, namely to 21%, then the reactance will be reduced to approximately two thirds of its original value, or about 20%, giving thus a total quadrature component of 41% in place of 44% for the full pitch winding, which means a material improvement in the power-factor, to say nothing of the increase in starting torque and break-down torque. Of course an appropriate reduction in the number of primary conductors would have approximately this same effect.

The extra insulation required by fractional-pitch windings would hardly be an item of any importance in induction motors of ordinary voltage, but might easily take on considerable proportions in high-voltage alternators.

A. S. McAllister: The problem of determining the exciting current or the " wattless volt-amperes " is rendered very simple when the solution is based on the fact that any energy that is magnetically stored in the field during any part of the cycle must be restored during the next part of the cycle, in any machine which has an alternating flux. Of course, the relation just stated does not hold in the case of the synchronous motor, where magnetic energy is initially stored in the exciting field but not given out during any part of the cycle. If, in the induction motor, we find the volume of the main magnetic path and divide it by the permeability, and find the volume of the teeth and divide that by the permeability, and find also the volume of the air gap and divide that by the permeability (which happens to be one) and multiply each of these values by the square of the flux throughout the respective paths, we can determine the value of the magnetic energy stored in each of the paths; this same magnetic energy is given out through each cycle. Therefore, the " quadrature watts " or the " wattless volt-amperes ", can be calculated just as one calculates the core-loss watts in a motor, or in any other apparatus in which the flux is alternating. This fact was mentioned during the Milwaukee meeting, at which time an equation was given for representing the actual value of the wattless volt-amperes.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907

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THE VECTOR DIAGRAM OF THE COMPENSATED SINGLE-PHASE ALTERNATING-CURRENT MOTOR

BY W. I. SLICHTER

Although the compensated single-phase motor is simply a series circuit in physical connection, there are incidental reactions which have the effect of a combination of series and parallel circuits. These reactions have an effect on the efficiency and power-factor of sufficient importance to warrant a careful analysis of their character and cause.

As is well known, the motor circuits consist of an exciting field winding producing the field flux, an armature similar to that used in the usual direct-current motor, and a compensating winding wound in the faces of the poles and having its magnetic axis coincident with the axis of the armature reaction, but producing a magnetomotive force in the opposite direction. Thus, in Fig. 1 is shown the diagram of connections of a four-pole compensated series motor. F, FF is the exciting winding with coils surrounding the pole pieces, C, CC is the compensating winding from pole to pole; and A, AA is the armature circuit. The current passes through these three in series, and the main reactions of one member on the others are very simple.

But the coil in the armature undergoing commutation encloses the main exciting or torque-producing flux, and, as a result of the alternation of this flux at primary frequency, there is induced in the coil an electromotive force proportional to the primary frequency and to the magnitude of the flux. The brushes complete the circuit of this coil, and a current flows therein proportional to this electromotive force and inversely proportional to the impedance in the coil, brushes, and connections. This reproduces exactly the conditions existing in a transformer, the exciting winding F being the primary and the short-circuited coil BB being the secondary, as shown in Fig. 2.

In considering the reactions in the exciting winding, therefore, we must regard it as a complex circuit. The effect is the same as if the coil were shunted by an equivalent circuit having resistance and inductance, as at Y in Fig. 2. This equivalent circuit represents the hysteretic current, supplying the core-loss in the iron due to the alternation of the flux at primary frequency, and the current in the secondary coil BB.

Fig. 3 shows the relations of the various quantities in the exciting winding F. The resemblance to the transformer diagram will be noted. ϕ is the flux; the current which produces ϕ is $O\,F$, composed of $O\,B$ the wattless component and $O\,H$ the hysteretic component. $O\,A$ is the current in the secondary and this combines with $O\,F$ to form the primary or line current $O\,C = I_0$. $O\,E$, 90° ahead of the flux, is the electromotive force consumed in the primary circuit. Neglecting the impedance drop, which is very small in this case, the voltage across the terminals of the exciting winding is therefore $O\,E$.

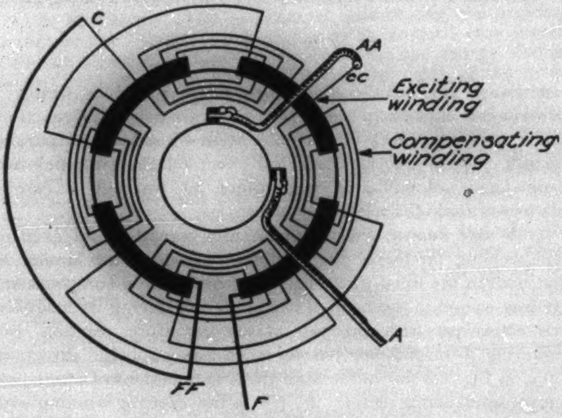

FIG. 1

In Fig. 4, we have this same diagram as a starting point for the general case. Thus, with a main current I_0, represented by $O\,A$, we have $I_H = A\,B$ for the energy current in the equivalent shunt circuit, and $I_M = O\,B$ the wattless component in both the primary and shunt circuits, but consisting principally of the primary magnetizing current.

The flux ϕ is in phase with $O\,B$ and proportional to this primary component of $O\,B$ (not to the main current) and the permeance of the magnetic path.

The electromotive force induced in the exciting winding is $I\,X_M = O\,E$, and is 90° ahead of ϕ. The electromotive force consumed by the leakage reactance of all the windings will be 90° ahead of I_0 and proportional to I_0. This is represented by $I\,X_L = E\,F$. The electromotive force consumed by resistance is $I\,R = F\,G$, in phase with I_0.

The counter electromotive force due to the rotation of the armature conductors in the flux must be in phase with ϕ, thus $G\,H = e_2$ (drawn parallel to $O\,B$) represents this electromotive force in phase, while its magnitude is proportional to the angular speed of the armature.

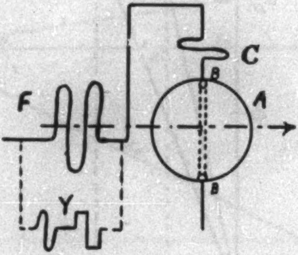

FIG. 2

The line potential E_0 is the resultant of all these components. Its magnitude determines the value of e_2, which in turn determines the speed. $O\,H$ represents the line potential, and the cosine of the angle $H\,O\,A = \gamma$ between E_0 and I_0 is the power-factor of the motor.

The product of $e_2\,I_0 \cos\alpha$ represents the output at the armature conductors. To obtain the true motor output, the armature core-loss, due to rotation, and the friction loss should be subtracted from this.

The calculation of power-factor and efficiency is made by starting with the displacement angle α whose sine is $I_H \div I_0$. Assuming the phase of I_0 as a reference point, we have the following resolution of the terminal electromotive force E_0:

Wattless	Energy
$I\,X_M \cos\alpha$	$I\,X_M \sin\alpha$
$I\,X_L$	$I\,R$
$-e_2 \sin\alpha$	$e_2 \cos\alpha$

The exact analytical expression of the reactions is as follows: Assume $e = I\,X_M$ the voltage across the exciting winding as reference vector or zero phase.

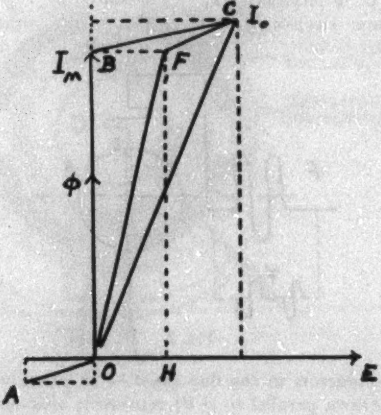

Fig. 3

Quantitatively $e = 4.44\,n\,N\,\phi\,10^{-8}$
where: n = primary frequency.
N = number of exciting or field turns.
ϕ = flux per pole.

Admittance of exciting winding = $Y_1 = g_1 + j\,b_1$
Admittance of equivalent circuit = $Y_2 = g_2 + j\,b_2$
Admittance of combination $Y_x = Y_1 + Y_2 = g_x + j\,b_x$
Main line current = $I_0 = e\,(g_x + j\,b_x) = i_1 + j\,i_2$
Resistance of all circuits = r
Reactance (leakage) of all circuits = x
Impedance of motor (except exciting circuit) = $Z = r - j\,x$

Line voltage = E_0 is resolved into electromotive force of rotation e_2, electromotive force of excitation winding e, and the impedance voltage $I_0 Z$.

e_2 is in phase with the flux ϕ and 90° from e; therefore, if e is the base of vectors, the electromotive force of rotation is expressed in phase position by $j\,e_2$.

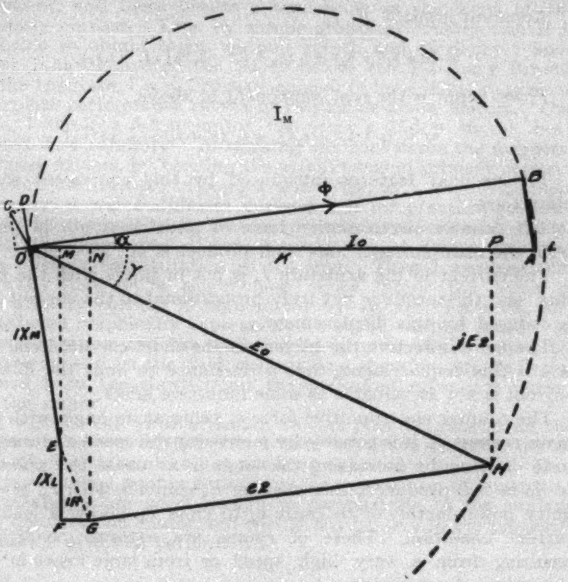

FIG. 4

Hence $E_0 = e + j\,e_2 + I_0 Z$
Substituting:

$$= e + j\,e_2 + (i_1 + j\,i_2)\,(r - j\,x)$$

$$= e + i_1 r + i_2 x + j\,(e_2 + i_2\,r - i_1\,x)$$

Reducing to absolute terms:

$$E_0^2 = (e + i_1 r + i_2 x)^2 + (e_2 + i_2\,r - i_1\,x)^2$$

Solving for e_2:

$$e_2 = \sqrt{E_0^2-(e+i_1r+i_2x)^2}-(i_2r-i_1x)$$

The output at the armature conductors is the product of the counter electromotive force and the current in phase with it, $e_2\, i_2$.

Apparent input $= E_0\, I_0$

$$= [e+i_1r+i_2x+j\ (e_2+i_2r-i_1x)]\ (i_1+j\, i_2)$$

Power input is the real component of above.

$$= i_1\ (e+i_1r+i_2x)\ +i_2\ (e_2+i_2r-i_1\, x)$$

The peculiar features introduced by this equivalent shunt circuit are:

The counter electromotive force of rotation is not in phase with the main current, thus their product is not all energy.

The current in the armature I_0 is not in phase with the field flux, and the torque is not truly proportional to the current but is reduced by this displacement.

The more inductive the current in the short-circuited coil the less is this displacement, thus a resistance to limit the flow of current is not as valuable as some inductive effect.

The counter electromotive force e_2 being at an angle with the main current I_0, it is possible by increasing the speed and magnitude of e_2, or by increasing the angle α, to cause the point H to lie in $O\,L$ produced, thus making E_0 coincide with I_0, giving unity power-factor, or to cause e_2 to cross I_0, giving a leading current condition. These of course are extreme conditions resulting from a very high speed or from large losses in the equivalent shunt circuit.

The wattless component of the counter electromotive force $(-e_2 \sin \alpha)$ has a marked effect on raising the power-factor, considerably more than the mere addition of the amount of energy which causes the phenomenon.

DISCUSSION ON "THE VECTOR DIAGRAM OF THE COMPENSATED SINGLE-PHASE ALTERNATING-CURRENT MOTOR", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

V. Karapetoff: In the year 1904, I contributed to the Institute TRANSACTIONS a complete performance diagram of the series single-phase motor. The diagram is similar to the well-known circle diagram of an induction motor. Assuming the permeability of iron as constant, the reactance of the motor is constant, and there results a semi-circle as the locus of the primary current. Then by simple graphical construction it is possible to obtain input, output, speed, and efficiency. Soon after I had delivered the paper before the Pittsburg Branch of the Institute, I was fortunate enough to have in my possession complete performance curves of two single-phase motors. One was, I think, a 5-h.p. motor, the other a 25-h.p. motor, both tested very carefully. In working out backwards the diagrams of these motors, by plotting the actual locus of primary current, I found that instead of being a semicircle, as it should be theoretically, it was a different curve which for practical purposes could be assumed to be the arc of a circle, considerably flatter than the semicircle. Upon investigation, I found this was due entirely to saturation in the iron. Then I assumed empirically that for a single-phase series motor the locus of the primary current is represented by an arc of a circle, and I deduced graphically expressions for input, output, speed, etc. The saturation and the variation of permeability which it involves depend on the field current, and therefore can be determined from the short-circuit curve (locked saturation curve) of the motor.

I wish to call your attention to this fact, because in all the literature on the subject that I have happened to come across the effect of saturation has not been taken into account. Diagrams of series motors derived on the supposition of a constant permeability are good enough to demonstrate to the student the theory of the motor, but should not be used in the predetermination of actual performance.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907.

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TRACK-CIRCUIT SIGNALING ON ELECTRIFIED ROADS.

BY L. FREDERIC HOWARD

Railroads signals may be divided into three general classes according to their functions: (*a*) Those which confer rights on trains, or restrict their rights, known as train-order signals; (*b*) Those which designate the route a train is to take, and insure the safe condition of all switches and opposing signals on such route, known as interlocking signals; (*c*) Those which are used primarily for properly spacing trains, known as block signals.

Originally the operation and control of all these classes was wholly manual. Owing to the fallibility of the human agency, however, and also on account of the greater scope of protection to be secured, means were gradually devised to take from the operator under certain conditions the power to clear signals, while permitting him at all times to restore them to, and retain them in, the stop position. In some cases the signals were taken from his control altogether and made automatic. Means were also devised to prevent the operation of any switch while a train was approaching or passing over it.

It will therefore be seen that there are three distinct types of signals according to method of control; namely, the manual or non-automatic, the controlled manual or semi-automatic, and the purely automatic. Train-order signals are of the first type, interlocking signals of the first and second types, while block signals are of all three types.

The track circuit is by far the best expedient for effecting the control of the signal operator, and the power-operated block signal. It is used largely in connection with the latter; and as a means for dispensing wholly with the human agency, and providing the safest and most practicable method of automatic control will, for some time to come, remain the essential part of the automatic signal system.

Beyond the track circuit are the various signals, switches, and other appliances, operated mechanically or by pneumatic or electric motors of various types. These are the parts used by the signal engineer in his art of increasing the capacity of a road for the safe handling of traffic over the miles of main line, and for safely accomplishing the maximum number of train movements in the least possible time, with the least cost for maintenance and operation in complicated yards and terminals.

The track circuit being the factor upon which the signal engineer primarily depends for the automatic control of his apparatus, the use of the rails on electrically operated roads as common conductors for both signal and propulsion currents has brought to the front new conditions and new apparatus in connection with the track circuit, with which it is advisable that the electrical engineer should become acquainted. In this paper I shall try to trace the development of track-circuit apparatus which has taken place in less than a decade, and give some idea of the relations existing between the track-circuit system and the propulsion system on electrified roads.

The track circuit, as it exists in its simplest form on steam roads, is shown in Fig. 1, except that the gravity cell is generally the source of electric energy. The storage-battery is rapidly coming into use for this service, however, and is shown in Fig. 1, better to illustrate the relations of the elements constituting the track circuit. These elements are: a source of electromotive force; a series resistance (comprised in the battery itself when the gravity cell is used); the rails forming the conductors, and insulated from the adjacent rails at the ends of the section, and in multiple across the rails the resistances of the relay, ballast, and ties. When the track section is occupied, there is another resistance in multiple with the foregoing; *i.e.*, that of the wheels and axles of the train.

Through the contacts of the relay are passed the circuits which control the apparatus governing admission to the section; as, for instance, the semaphore signal shown in the figure.

For convenience, the reciprocal of the resistances, or the conductances, of the ballast, ties, wheels, and axles will be used in much of what follows.

The circuit shown in Fig. 1 differs from those with which the electrical engineer ordinarily has to deal, in that it is operated by shunting, instead of disconnecting, the source of electric energy. This makes necessary the consideration of the relation of the operating shunt to the other elements of the circuit.

The " ballast conductance " (which is considered as including the conductance of the ties) is a variable, and for any given section its value depends upon the weather.

Suppose that the voltage across the terminals of the relay at which its contacts close is practically the same as that at which they open; or, as the signalman would say, that the " pickup point " is the same as the " shunting point". This supposition corresponds closely with the facts in the case of alternating-current relays, where motion may be considered as due to the reaction between currents, but is not true of the ordinary attracted armature direct-current relay where the shunting point is approximately one-half the pickup point. Suppose further that when the ballast conductance is at its highest value, as during wet weather, the track circuit is so adjusted that the relay just picks up. It is evident that when the ballast conductance has diminished, because of the moisture drying out or freezing, a conductance equal to the change in the value of the ballast conductance must be added between the rails in order to cause the relay to shunt.

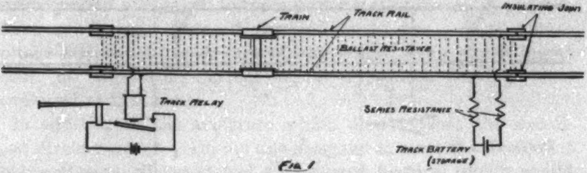
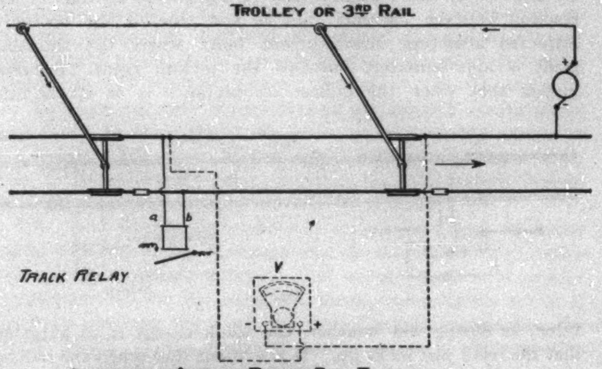


FIG. 1

If the contacts of the relay must be open when a single car is in the track section, the reciprocal of this change of conductance determines the resistance from rail to rail allowable in the wheels and axles of the single car. This, in turn, determines the length of section which can be operated, as the change in ballast conductance due to weather conditions varies directly with the length of section. In practice the limit of power available for supplying the track circuit is usually reached before the shunting limit, as the length of the section increases.

In considering the source of electrical supply for the track circuit, and its series resistance or equivalent, it should be noted that the higher the voltage of the source, the higher the value of the series resistance necessary, and consequently the greater percentage variation in voltage across the relay with a given change of conductance between rails. The higher voltage means, then, a greater factor of safety as regards any variations in the shunting point of the relay, but also subjects the relay to wider variations of voltage.*

About eight years ago the Boston Elevated Railway Company had its new elevated lines nearly ready for operation and wanted them protected by a track-circuit automatic block signal system. The motive power was to be direct current at 550 volts and with ground return. One rail at least was to be continuous; that is, not divided into sections by insulated joints. Here, then, was a new condition of affairs with one of the rails of the signal circuit traversed by a foreign current of comparatively enormous volume.



POTENTIAL ACROSS RELAY DUE TO RETURN POWER CURRENT

FIG 2.

Fig. 2 shows at once the difficulty which the signal engineer encountered. The power generator is represented by the conventional symbol. *V* represents a voltmeter which as connected will measure the drop of potential due to the flow of return propulsion current over the continuous rail. Now with a train at the far end of the block from the relay, the latter has the same potential across its terminals as that measured by the voltmeter, for lead *a* connects one side at the same point as the positive lead of the meter, and lead *b*, the insulated rail, the wheels and axles connect the other side to the same point as the negative lead of the meter. Whether or not an ordinary electromagnet type of relay will close its contacts under these conditions depends on whether or not the voltage at which it is adjusted to operate is greater than the drop of potential caused by the return of power current over the length of rail measured by the length of block. In the case of the Boston Elevated the maximum drop which could occur over the return rail was limited, owing to the facts that the blocks were short and the return rail was bonded at close intervals to a structure having a copper equivalent of 14,000,000 cir. mils, from which the return current was taken to three power stations suitably spaced. These conditions made it permissible to use a relay whose voltage adjustment took care of any return drop which might occur, no alternating-current signal apparatus having been developed at that time.

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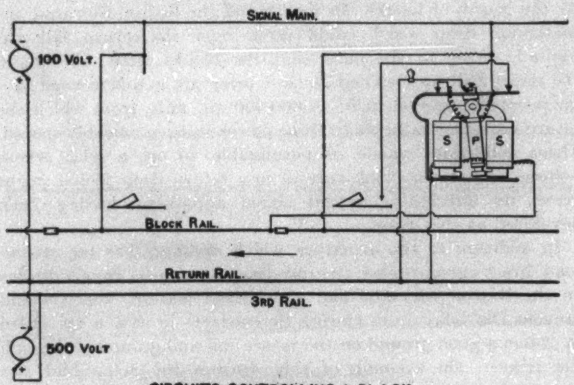
*This subject of track circuits was taken up by Mr. H. G. Brown in a paper read before the Institution of Electrical Engineers, last December.

In addition to the armature which distinguishes the steam-road direct-current relay, the one designed to meet the conditions on the Boston Elevated had a polarized feature, which would prevent the relay from closing its contacts in case a car failed to obtain a good ground on the return rail and grounded through the relay. On account of this feature the relay had two separate and distinct sets of magnets as shown in Fig. 3. The stationary set, *SS*, is connected across the rails; the swinging set, *P*, is connected to the main leading to the negative pole of the signal generator, the positive pole of which is grounded. This generator replaced the batteries used on the steam road.

Supposing the relay to have de-energized, the sequence of operations in closing the relay contacts is as follows: the signal current coming from the positive pole of the generator, via the return rail, passes through the stationary coils to the block rail; thence through the latter via the resistance to the negative signal main. This picks up the armature which closes the left-hand contact and completes the circuit through the swinging coils. The polarity of the latter being fixed, they will swing to the right, if conditions are normal, bending the phosphor-bronze strip to which they are rigidly attached. This closes the circuit to the local control mechanism through the upper right-hand contact.

If the propulsion current from the car motors fails to obtain a ground on the return rail but flows through the stationary coils of the relay, their polarity will be reversed on account of the propulsion current flowing in the opposite direction to the signal current. This will cause the swinging coils, whose polarity remains fixed, to move to the left and open the right-hand control contact.



CIRCUITS CONTROLLING A BLOCK.
BOSTON ELEVATED RY.
FIG. 3

This Boston Elevated signal system comprises some 90 odd track circuits and 170 blades, including interlocked signals, and about 60 switches, the latter being distributed among five electropneumatic towers and two mechanical towers.

The next electric road to be equipped with signals was the North Shore Railroad near San Francisco. On this road several of the blocks were to be over 4000 ft. long, and there was to be a maximum of 8 trains of 4 motor cars each, taking about 1600 amperes per train at starting. The power station was to be in the middle. In this case there was no elevated structure of 14,000,000 cir. mils capacity to take care of the return drop of the power current, so the first alternating-current track circuit was installed.

The system used was what is termed the alternating-current single-rail return, and is shown in Fig. 4. The direct-current generator of the Boston Elevated is replaced by an alternating-current generator or transformer, stepping down from propulsion power mains to a suitable voltage for transmission of current over the two signal mains. Instead of supplying the track circuits directly from the signal mains through a resistance, a step-down transformer is used with a resistance in its secondary.

At the other end of the track section is an alternating-current relay, of the type shown in Fig. 5. It consists of a *C*-shaped laminated core carrying a winding connected across the rails. One half of each pole-piece of the core is enclosed by a copper ferule. Between the faces of the poles is a sector of aluminum rotating on a shaft at right angles to its own plane. The shifting magnetic fluxes in the pole-pieces cause the rotation of the vane according to the well-known Ferraris principle, when sufficient alternating current passes through the winding to overcome the counterweight on the aluminum sector. The shaft carries the contacts. This relay, of course, is immune to direct current so far as the operation of its contacts goes. To limit the direct current passing through it to an amount below that

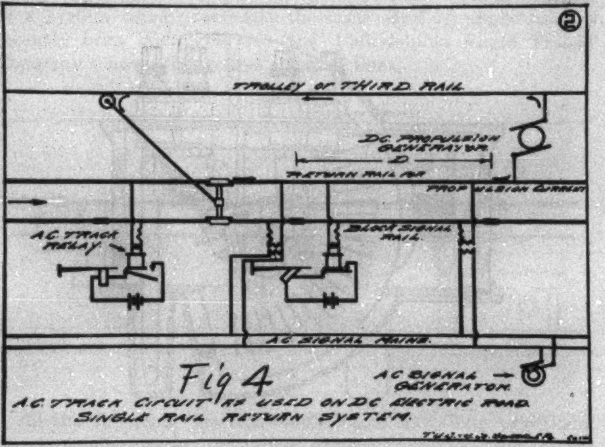


Fig 4

A.C. TRACK CIRCUIT AS USED ON DC ELECTRIC ROAD SINGLE RAIL RETURN SYSTEM.

which would dangerously heat it, or saturate the iron, the relay is shunted by an impedance coil, and a resistance is also inserted in one end of the leads. Going back to the other end of the track section, it is seen that the resistance in the secondary leads of the transformer is assisting to prevent the flow of direct current through the secondary winding of the transformer, in addition to its other functions in connection with the adjustment of the track circuit.

The track transformer and the impedance coil across the relay terminals are furthermore made with open magnetic circuits to keep down the density of magnetization caused by the flow of direct current, due to drop of potential over the continuous rail spoken of in connection with Fig. 2.

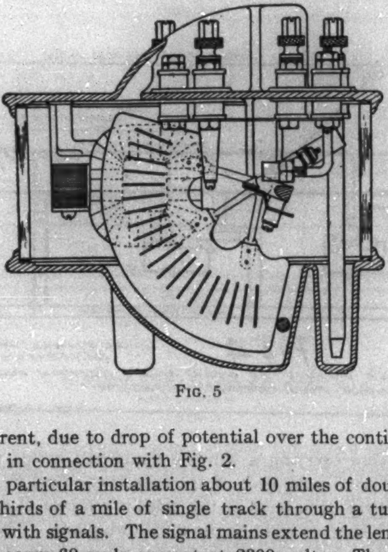


FIG. 5

On this particular installation about 10 miles of double track, and two-thirds of a mile of single track through a tunnel, were equipped with signals. The signal mains extend the length of the road and carry 60-cycle current at 2300 volts. They are supplied from the step-down transformers at the power house. One of the track sections is over a mile long.

The description of the foregoing system applies equally well to the system installed in the New York Subway, so far as the alternating-current track circuit is concerned.

The greater volume of direct current to be taken care of in the latter system was offset by the number of tracks, the steel framework of walls and roof, the close spacing of the sub-stations, and the shorter blocks. The signal mains are supplied with 60-cycle, 500-volt current by transformers located in the sub-stations, and stepping down from the high-voltage lighting mains. In emergency, 25 cycles stepped down from the propulsion circuits is used.

The New York Subway system comprises some 500 track circuits, 700 signals, and 230 switches, and has a record of one failure of apparatus to 3,359,167 movements, with no false safety indications in more than two years. The installation of a system using practically the same kind of apparatus has recently been completed on the Philadelphia Rapid Transit Company's new subway and elevated lines.

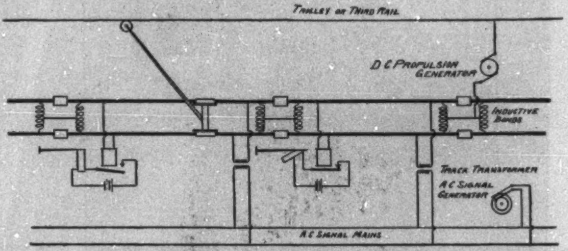


FIG 6

All the foregoing systems necessitated installing additional return conductors for the power current to compensate for the rail given up to the signal system, except where an elevated structure was available. The possibility of the use of a track circuit in which both rails should be used in common for signal and propulsion currents had been contemplated before this time. Local conditions on the Boston Elevated, the North Shore, and the New York Subway had made the single-rail system acceptable, however, and this led to deferring the development of the two-rail system shown in Fig. 6.

A path for the propulsion current around the insulating joints is provided for in the two-rail system in the form of the impedance bonds indicated in the figure. It is apparent that as the propulsion current divides so that each part passes around the iron core of the bond in opposite directions, its magnetizing effect on the core is zero, so long as the current divides evenly. On the other hand, the full impedance of the bond is offered to the signal current in preventing its passage from rail to rail.

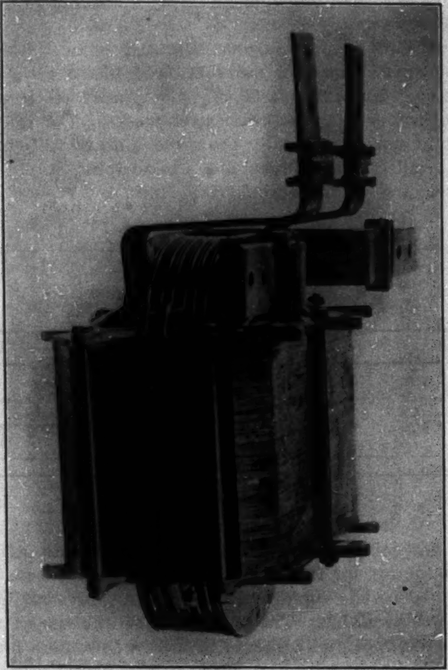


FIG. 7

Fig. 7 is a view of the bond out of its case. It consists of a shell-type core and heavy strap copper winding. The effect of unbalanced direct current is provided for, up to limits well beyond those met on properly bonded tracks, by using an open magnetic circuit and working the iron so far down on the saturation curve that the impedance of the bond actually rises with a small amount of unbalancing. These bonds may be installed between the rails of a track, as shown in Fig. 8, or just to one side.

The track transformers for this system are designed to have excessive magnetic leakage, and consequently a rapidly falling secondary characteristic, thus dispensing with the series resistance used with the battery or generator of the direct-current track circuit, or transformer of the single-rail, alternating-current track circuit

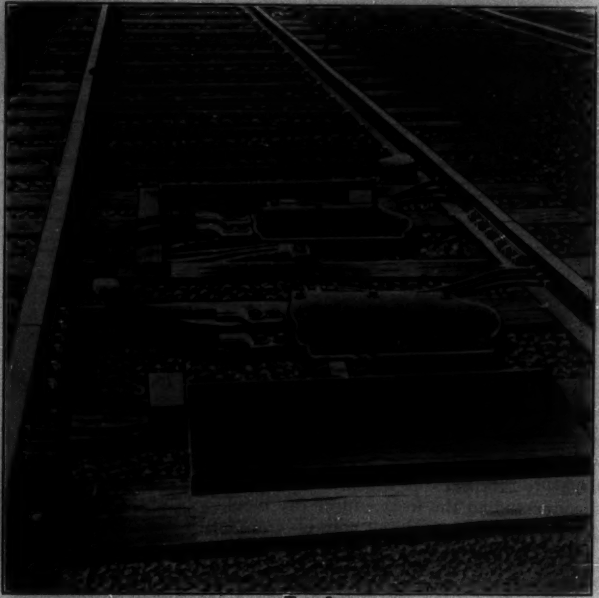


FIG. 8

Again the Boston Elevated was the scene of the installation of a new system, about 14 blocks of this type being installed during the winter of 1904–5, in the tunnel under the harbor, between Boston and East Boston.

The next installation of the double-rail return was on the electrified lines of the Long Island Railroad. The requirements here were 1100 amperes of return propulsion current per rail, and 800 amperes unbalancing. The track transformers and relays were grouped as shown in Fig. 9, instead of being placed at opposite ends of the blocks. 2200-volt mains carrying 25-cycle current supply a commercial 2200 to 55-volt transformer at each group of track transformers.

About 140 track circuits were installed and 19 miles of double-track road and 4.5 miles of four-track road were equipped with signals.

Last fall a third installation of the double-rail system was completed; namely, that on the West Jersey and Seashore Railroad. The sub-stations were to have a maximum ultimate capacity of 7000 amperes each, which, if distributed equally over the four rails, would mean 1750 amperes per rail.

The blocks were about 4000 ft. long and the innovation was introduced of placing the track transformer at the middle of the block (Fig. 10) with the relay at one end and a small step-up transformer at the other. The relay is really a motor with the armature rotating through about 45 degrees. The field winding is connected to the near end of the block, and the armature to the secondary of the small step-up transformer at the far end.

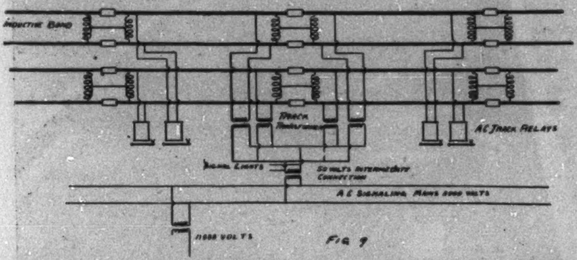


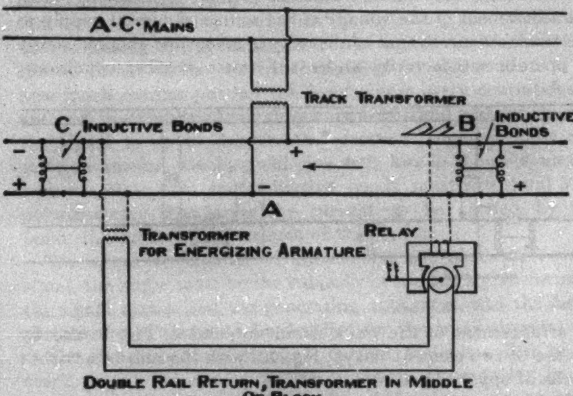
Fig 9

At each sub-station on the section equipped, a transformer between one leg of the power mains and the ground steps down to 1100 volts for the signal mains, which are carried on the poles below the power mains.

The signal system being installed in the electrified zone of the New York Central and Hudson River Railroad is also a two-rail system, using inductive bonds connected as in the systems described, but the relay is a two-phase induction motor with one phase fed from the track circuit, and the other from the signal mains, the difference in phase being obtained by the proper combination of the elements of the two circuits.

Having thus briefly described the different track circuit systems in operation on electrified roads, it is of interest to recall the discussion given in the earlier part of the paper of the simpler form in use on the steam roads, and then consider the changes made in some of the elements of the track circuit by the use of the double-rail return system. The latter system is chosen for discussion, as it constitutes the latest and most radical departure from the simpler form.

By the use of an alternating signaling current, we have an increase in the apparent resistance of the rails, due partly to skin effect and partly to magnetic induction. This increase is of course a function of the frequency.



Double Rail Return, Transformer In Middle Of Block
Fig. 10

We have also introduced an artificial apparent conductance between the rails in the inductive bonds, and they, together with the relays, introduce another inductive component.

The increase in the apparent resistance of the rails means, of course, higher voltage at the source of supply for the track circuit, and consequently more power. On account of the higher impedance of the rails and the consequently higher voltage required at the source of the supply of the track circuit, other things being equal, a given shunt applied to the rails at the relay will produce a larger percentage change of voltage across the terminals of the relay.

On the other hand, where relays with a single winding are used, and there is leakage around an insulation joint from an adjacent block, a train at a given distance beyond the relay has less shunting effect on the relay, and there is greater danger of getting a clear signal with a train in the block, than with the direct-current track circuit.

This may be seen more clearly by an inspection of Fig. 11. The insulating joint, *A*, is defective, and current from the section on the right, flowing as indicated by the arrows, will tend to make relay *R* close its contacts. The resistance of the rails between the shunt, *S*, and relay, *R*, diminishes the effectiveness of the shunt as the effective resistance of the rails increases.

This danger may be diminished in various ways, among which are adjustment of the voltage of the source of current supply to the track circuit, so that to the relay is given just enough energy to operate satisfactorily under the worst weather conditions; by arrangement of the track circuit apparatus, Fig. 9; and by the use of two element relays, Fig. 10, with the rails of adjacent blocks of opposite polarity.

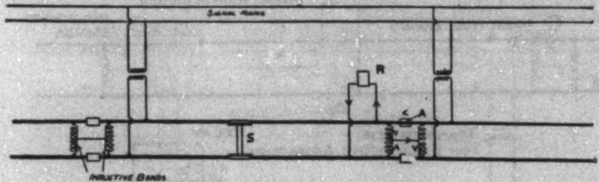


FIG. 11

When two-element relays are used, they should be as free as possible from any tendency to close the contacts because of repulsion or induction motor effects, caused by normal or accidental short-circuiting. In some forms of frequency relays the effects of open circuits must also be guarded against.

The introduction of artificial apparent conductance between the rails by the use of inductive bonds also has its advantages and disadvantages. Principal among the advantages is the smaller percentage change in voltage across the relay due to changes in ballast conductance with varying weather conditions. For the same reasons the shunt produced by the train causes less percentage change in voltage across the relay.

These two effects may be taken advantage of in the design of the transformer supplying the track, by making its secondary characteristic with a steeper gradient than where the bonds are not used. The greater the apparent conductance of the bond, the steeper should be the gradient.

The principal disadvantage arising from the introduction of the apparent conductance of the bonds between rails is the extra amount of current taken and the consequent drop in voltage between the track transformer and the relay, with the resultant increase in leakage through the ballast.

It is at this point that the electrical engineer laying out the power system for a road which is to use direct-current propulsion should realize that the higher the efficiency of his return system the cheaper will be the signal system, both in first cost and operation; and when the signal engineer of the road who is making up specifications for the signal manufacturers to bid on comes to the electrical engineer for information as to how much current per rail the bonds must carry continuously, and how much unbalancing they must withstand without causing the signal to go to danger, the electrical engineer must not state an amount which would give 40% loss in the rails, and in addition state that the inductive bonds must withstand 50% unbalancing. The larger the current to be carried by the bond, the greater the first cost of the copper.

The larger the amount of unbalancing the bond must withstand, the larger must be the capacity of the track transformers, the signal mains, and the generating apparatus, and the larger the amount of power to be supplied for the track circuits.

The greater amount of signal current to be supplied to the track circuit because of greater unbalancing capacity in the bonds is due to the fact that this unbalancing capacity is obtained by widening the air-gap in the magnetic circuit of the bond. This of course increases its apparent conductance and the current demands on the track transformers.

With roads using alternating-current propulsion, this unbalancing becomes of minor importance; first, because the return propulsion current is so much smaller; secondly, because the propulsion current being alternating, the actual resistance of the rail has a small ratio to the apparent resistance, and a comparatively large difference in the actual ohmic resistance of the two rails of a track may exist without making any great change in the propulsion current values in the two rails.

The inductive bonds for roads using alternating current for propulsion can therefore be made without an air-gap, and the only effect of unbalancing is to produce a voltage across the terminals of the relay of the same frequency as the propulsion current. This voltage being small with any reasonable amount of unbalancing, it may be taken care of in the frequency relay.

This frequency relay is so constructed that the presence of a voltage across its terminals of the same frequency as that of the propulsion current will not close the relay contacts, the presence of a higher frequency signaling current being necessary to accomplish this result.

The difference in unbalancing effect on roads using direct-current propulsion from that on roads using alternating-current propulsion, together with the higher frequency signaling current, made necessary when alternating-current propulsion current is used in order to operate the frequency relay, constitutes the principal differences in the relations between the elements of the track circuit as used on the two systems; so that what has been written of the double-rail track circuit on the direct-current road applies equally well, with the exceptions noted, to the same system on the alternating-current road.

DISCUSSION ON "TRACK-CIRCUIT SIGNALING ON ELECTRIFIED ROADS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907.

Charles F. Scott: This paper is quite special in its scope and is valuable for the information it gives, but is not apt to be fruitful of general discussion. I have been interested to note during the reading of the paper, and also in my observation during the last few years of this signal development, the general course of that development and the effect of the electrification of railways on signal work. At first, on the ordinary steam road, the only electricity used in connection with the track system was the small amount employed in connection with the signals. The use of the track, however, for carrying direct current for railway motors has caused some voltages to be introduced which begin to affect the signal circuit and they have to be taken care of in ways which when they are worked out and explained seem simple and adequate, but did not seem so simple when the difficulties first arose. The introduction of single-phase alternating current and the use of the rails for conducting this current again introduces a new kind of disturbance in the signal system. It is interesting to note how the signal work has followed these various intrusions of greater currents. One rail was set aside for signal work, and later on the signal system adapted itself to the condition existing when both rails were used for propulsion current. The signal engineer follows the example of the railway engineer and gets into alternating current; if the alternating current in the railway is bad for his work he cures the evil by adopting alternating current himself. He solves the frequency question by going to a high frequency instead of a low one. This also illustrates the amount of electrical engineering which can be applied to what most of us who have not come in contact with this work at all have probably considered a very simple sort of thing, but the grade of engineering work and the knowledge and ingenuity required in devising these systems, with the remarkable reliability and excellent way in which they perform their work, is something to elicit our admiration.

There is still another source from which other currents may come and affect the signals, which I understand has been characteristic of one installation, and that is when the tracks were bonded together for the operation of the railway these track connections formed an inviting path for currents from adjacent railways which were strolling through the earth, hunting convenient paths by which to get home, and these currents got into the tracks and the signal apparatus producing some unexpected combinations of signals. This illustrates again the interference between different kinds of currents and the need of the signal engineer to be alert for their avoidance.

Henry G. Stott: I think we ought to be congratulated on the presentation of a paper of this character. It is perhaps significant of the very small general knowledge on the subject of the signaling system which we have, that so few people are ready to discuss it. I am connected with a railroad which is using the type of signaling described in Mr. Howard's paper, and I am perfectly free to admit that I know very little about it. We have a signal engineer, but his work is so specialized that it is an entire department by itself. If we all knew what signaling engineering is and the mass of details with which the signal engineer must contend and the wonderful ingenuity which he displays in arranging them, I think we would put the signal engineers at the very top of the class instead of the bottom.

In the first operation of the signaling system on the Subway in New York City considerable difficulty was encountered, due to the fact that the source of supply of the current was one which had variable electromotive force. The 60-cycle current was generated by a generator coupled to a direct-current motor which was operated from the ordinary third-rail current and subject, therefore, to very wide fluctuations of voltage. That reacted, of course, to keep the tongues of the relays on the signal system almost in continuous vibration, thereby reducing the life, and in some cases with very wide changes, resulting in failures in the signal apparatus itself. We changed that over so that the current is now supplied directly from 60-cycle turbines and the regulation on that is one per cent. Since that time the failures of signals to operate have diminished so that they practically do not exist. I forget what the record is, perhaps Mr. Howard has stated it, but I believe it is about one failure of the signal to operate in three or four million.

It seems to me that this development of the complete block system has got to come to all railroads. Until such is the case the appalling accidents which have taken place on many of our main lines during the past year will continue, because in the operation of power plants, and in the operation generally of all important apparatus, we find now that the apparatus itself has improved to such a point that the failures are not of the apparatus but of the men who operate them. A man may go along perfectly for years, doing the same thing every day, and then he fails absolutely. For example, in the power plants with which I am connected, in three years we have had only one shutdown, and that was caused the other day by the gross blunder of a man, who has done the thing perfectly hundreds of times, failing to do what he should have done. He could not explain it and no one else could explain it. The more we can eliminate the human element from our signal system the more perfect it will become.

Charles A. Perkins: It seems to me that this paper calls our attention to the desirability of extending the block system much beyond the range of signals; it is desirable, not only that the signals should be given, but also that the obeying of the signal should be beyond the option of the engineer or motorman who is operating the train. I have been in an accident caused by the engineer on a following train running by a danger signal. In the multiplication of automatic schemes for safety, such a scheme should be included in the block and signal system. I should like to hear from Mr. Stott as to how far this has been accomplished.

Henry G. Stott: On the Subway system this feature is absolutely automatic. The man cannot run past the signal. If he does the brakes are automatically set and the current is cut off. It is absolutely impossible for him to run by the signal without its being known. He may do it once, but he is not likely to repeat the offence, because he has got to get down and go under the car and reset the air-brake valves under the car before he can start the car again. This means, when he gets to the end of the line, he has to make an explanation why he ran by the block, and that means he is laid off for a week.

L. F. Howard: I shall make a few comments on the matter of the automatic stop. It is used on the Boston elevated, and I believe there are a few automatic stops on the Chicago elevated system. The matter is also being agitated on some other roads. On surface roads it is more difficult to apply, on account of weather conditions, when it is down on the ground. A number of years ago it was suggested that an arm should extend from the signal mast when the signal was at danger, this arm to be so arranged as to engage with a glass tube or stop cock on top of the engine cab. The tube or cock being connected with the train pipe of the braking system, the breaking of the glass tube or opening of the cock, in case the engineman ran by a " stop " signal, would set his brakes.

There are, however, quite a number of points in connection with the use of train stops on surface roads as yet undecided, and the present general feeling amongst the officers of such railroads is to adhere to present practice and exercise closer checks on their employees.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907.

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SOME POWER TRANSMISSION ECONOMICS

BY FRANK G. BAUM

> In designing power transmission systems, it is always well to bear in mind that the ultimate development of the art and of the country has not yet been reached.

In the early days of railroading, the roads and equipment were not of the present trunk-line standard. Light rails, engines and cars, and unfenced right-of-way, and unballasted roadway sufficed. To construct, at that time, up to the present standard would have meant bankruptcy. Even now the manager or engineer, who would build his branch lines of the same standard as his trunk lines, would invite a receiver to take charge of the road.

The same conditions hold true for power plants and transmission lines. The wise manager or engineer builds to meet existing conditions, looking into the future as far as he can. He can not afford to build duplicate plants and lines for every case, nor build all his lines on private rights-of-way with steel towers and other refinements and safeguards. He can not afford to build a duplicate transmission line, at an additional interest cost of $5,000 per year, when the probability of an interruption, which will cause a loss of revenue of $500 per year to a consumer, is extremely remote.

It may not be as difficult to determine the proper power station and line to build when unlimited capital and ideal power conditions exist as when there is restricted capital, limited revenue, and low-priced power at the consumer's end. Although in the latter case the amount of money to be expended may be much less than in the former, even more thought is demanded of the engineer; for, in the former case, having ample resources,

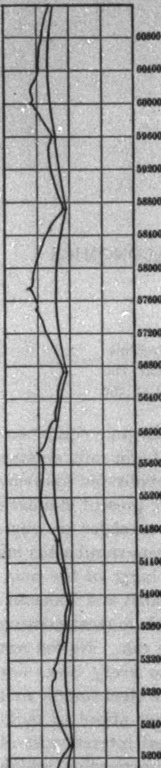


FIG. 1—Profile of Mountain Pole Line. Distances in ft

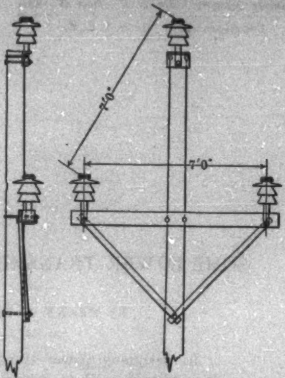


FIG. 2, Structure 1.—Spans up to 500 ft., 7-ft. triangle. Single construction. On corners, double arms and plates and one pin.

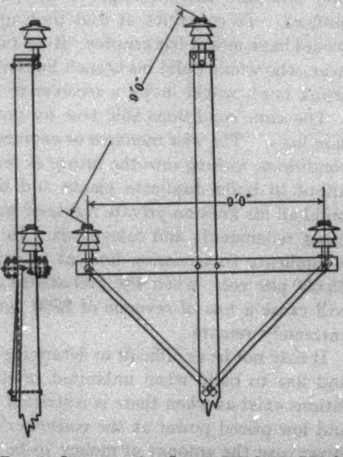


FIG. 2, Structure 2.—Spans 500 ft. to 700 ft., 9-ft. triangle. Double arms and plates, one pin. On corners, double arms and plates and two pins.

he builds as best he can, while in the latter he must be a judge of conditions and see far ahead, in order that the line which he builds may earn money and at the same time be capable of extension on some plan to meet the growing needs of the country and business.

To illustrate the necessity of doing things in inexpensive ways in the early development of an art, a business, or a country, some examples are given of the work done on the system of the California Gas and Electric Corporation. Along some of the lines where the load is small, one wire only is run to the sub-station, an inexpensive building, and one transformer, with ground return, is installed. One-phase motors are used. For larger stations, sometimes up to 500 kw., two wires are run to the sub-station and, by using ground return on the primary and open delta on the secondary, three-phase motors are operated.

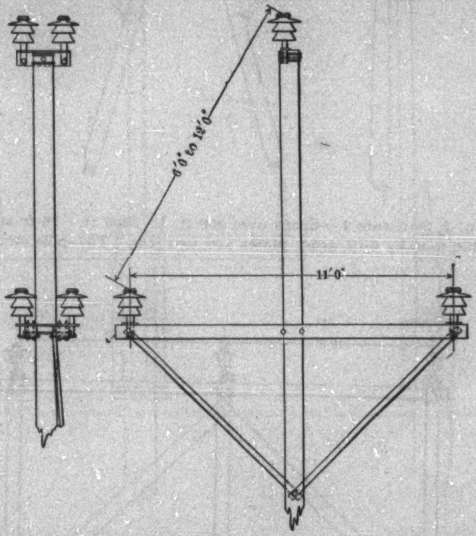


Fig. 2, Structure 3.—Spans 700 ft. to 900 ft. 11-ft. triangle. Double arms and plates and two pins. Corners special.

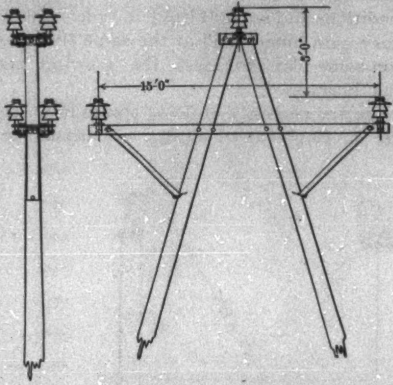


Fig. 2, Structure 4.—Spans over 900 ft. to 2000 ft. 16-ft structure. Double 6-in. by 6-in. arms, plates and two pins. Two-pole structure.

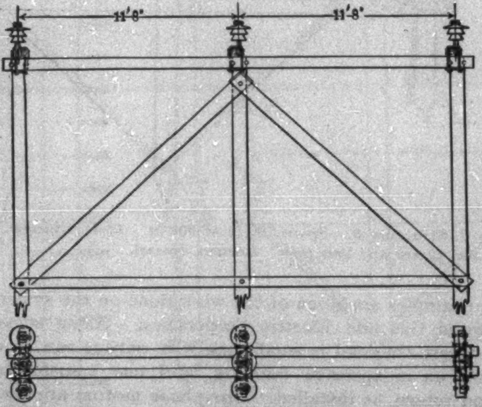


Fig. 2, Structure 5.—Spans 2000 ft. to 3000 ft. 24-ft. structure. Double 6-in. by 8-in. arms, plates, and three pins. Three-pole structure.

Loads as large as 1500 kw. have been carried to a distance of 100 miles on two transformers Y-connected on the primary, with grounded neutral, and open delta on the secondary. Neither the power consumer, nor the power-house operator has noted anything unusual.

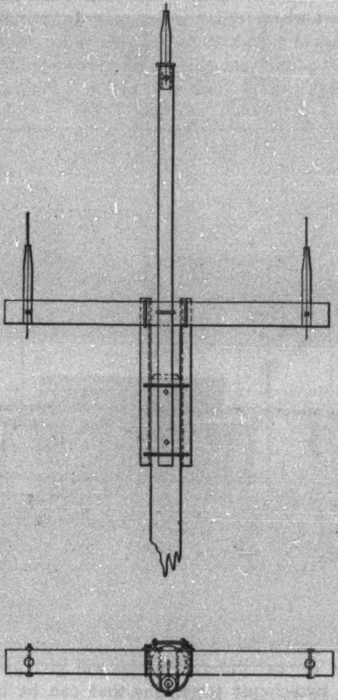


FIG. 3—Pole-top extension.

For larger sub-stations a single three-phase transmission line supplies the load, even where the length is 50 miles or more. The consumer can not afford to pay for a duplicate line when the output per year of the factory is practically unaffected by interruptions. Interruptions amounting to one hour per month would be one-seventh of one per cent. of the total time, and the power company that has an average of an hour's interruption per month is certainly giving very bad service. It is evident that the construction of a duplicate pole-line for such service is entirely unwarranted.

As to the construction of pole-lines, it has been found that in some parts of the West where cedar poles may be purchased at a low price, this class of pole-lines is still the most economical, and everyone must admit that this type of construction has proved remarkably effective. Of course under certain conditions tower lines only would be considered, but two wooden pole lines entering a city by two different routes will give greater reliability than any two-circuit tower line that can be built. The cost of a two-circuit tower line would be as great as that of two pole lines. A line using tower construction requires a private right-of-way, and in a new country it may not be possible to pay from the earnings the interest on the increased cost of the right-of-way as well as on the tower construction. The engineer, of course, always prefers the best construction, but he must consider the net revenue to be derived from an en-

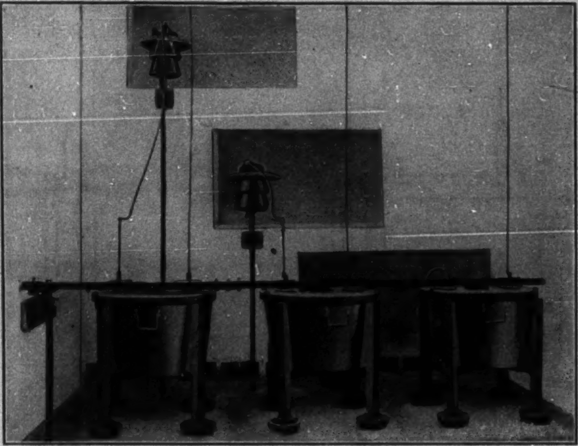


FIG. 4—Early type of oil-switch.

terprise in a given number of years. In mountain sections, the economies of line construction lie in the use of the hills for the structures and in using long spans. In some cases the amount saved in clearing, in poles, insulators, and labor will amount to 50%.

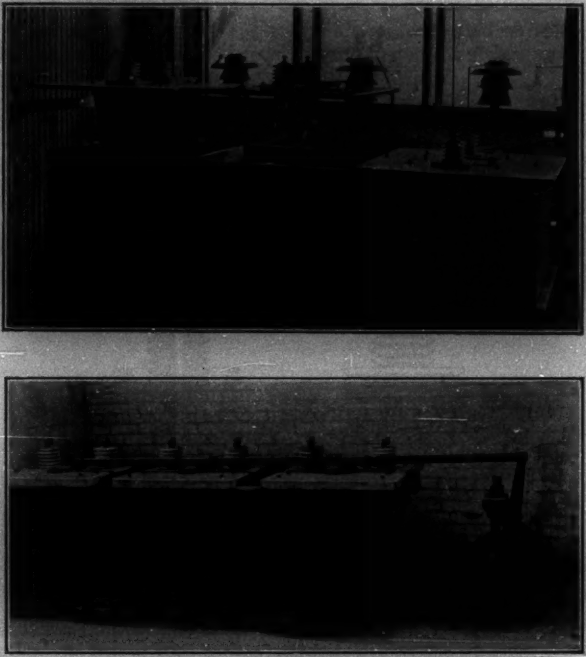


Fig. 5—Later types of oil-switches.

Fig. 1 shows a profile of a line recently constructed, the middle section of which consists of a series of spans varying in length from 700 to 2700 ft. It will be seen that by taking advantage of the hills to form the greater part of the height of the structure great economy results. A span of 3000 ft., with an allowable sag of 300 ft., would, if on the level, require towers over 300-ft. high, while, in this line on similar spans, simple wooden pole structures 30-ft. high are all that is necessary. The profile of a line of this kind is first determined, and the span-length and structures designed so that the wires clear the ground sufficiently. This gives an economical and satisfactory line

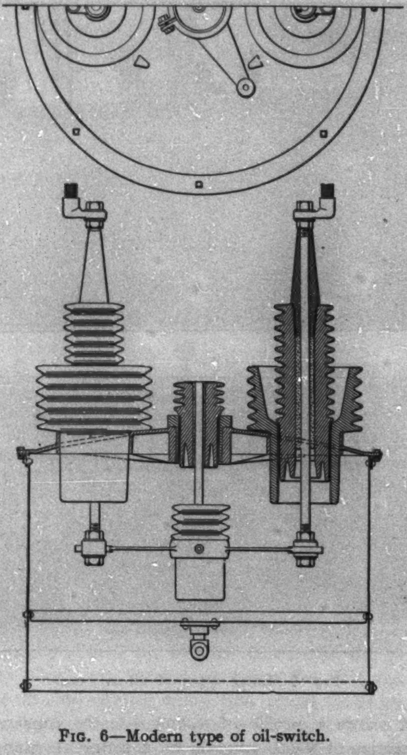


FIG. 6—Modern type of oil-switch.

On long spans the wires are spread at the structures as shown. In addition, the top or middle wire is given 10 to 40 ft. less sag (depending on the span) than any of the others. One of the outside wires is also given 5 to 20 ft. less sag than the other.

In this way there is obtained a vertical separation at the middle of the span; and 10 ft. of vertical separation is better than 20 ft. of horizontal, because the wires then can not come together even when acted upon by gusts of wind having a tendency to lift the wires. Spans greater than 2000 ft. are not installed exceptin certain cases where they can scarcely be avoided. Spans of 600 to 1500 ft. give the best line.

Fig. 2 shows standard types of pole structures used on some of the mountain lines recently constructed in California.

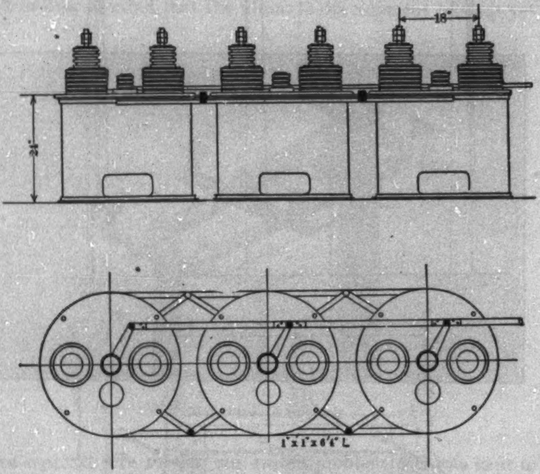


Fig. 7—Three-pole grouping of oil-switches.

Structures of this kind are sometimes also used for river crossings where the cost of steel towers is prohibitive or the time too short to install them. These are sometimes over 100 ft. high.

Referring to old lines which were constructed ten, or even five years ago, nearly all the lines were built with 40 poles to the mile, using 35-ft. poles. Now, the tendency is to use longer spans on account of the lower cost and the reduced number of insulators or weak points in the line. Some of these old lines have to be reconstructed later for a higher voltage, and, in order to obtain a reasonably good line and also to reduce the cost for insulators and future line maintenance, it is advisable in reconstructing to reduce the number of poles. To do this, the supporting points of the wires must be raised higher above the ground. In order to accomplish the result of reinsulating and reconstructing several hundred miles of line (which would have kept all the insulator factories busy for two years furnishing insulators for the old type of construction), the pole-top extension shown in Fig. 3 was used. This has proved effective. By using this pole-top extension, every other pole is taken out, with a saving of $9.00 per pole for new insulators and the additional salvage of the old poles, arms, pins, and insulators. Where sufficient height can be obtained by putting the arm below the top of the pole,

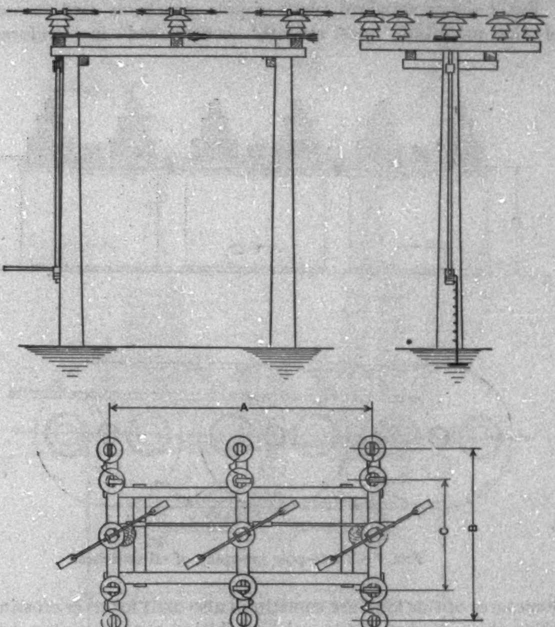


Fig. 8—Outdoor two-break air-switch.

this construction may be simplified in the fastening of the arm and pipe to the pole.

Another important adjunct of the transmission line is the switches, oil and disconnecting. It will be found that the same arguments regarding economical line construction apply to switches. Five years ago no one was sure of a high-tension switch and it would have been folly to install expensive switches of the first type that suggested itself without giving them a thorough trial during several years under operating conditions. In selecting switches and structures for high-tension lines, it is well to bear in mind that the ultimate development has not yet been reached. In solving our switch problem, this was kept in mind at all times.

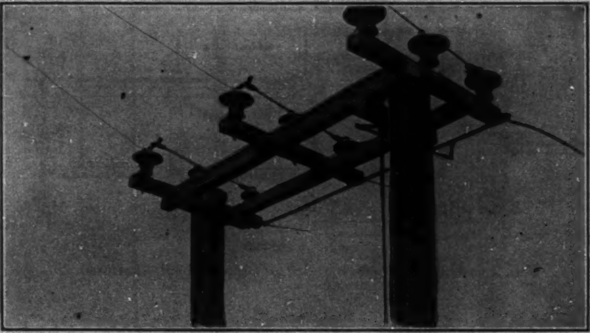


FIG. 9—Outdoor switch.

The first high-tension oil-switches were made as inexpensive and as simple as possible, and were as shown in Fig. 4. These operated so satisfactorily that we became convinced of the success of the type and soon changed to a more substantial form, as shown in Fig. 5. They are generally installed for hand-operation.

Although we have more than 100 of these switches on our lines, nearly 1000 miles at 60,000 volts all tied together, and over 50,000 kw. in generators operating on the lines at all times, the switches although cheaply constructed have given excellent results. All line switching is done on these high-tension switches, and the plants and lines are separated thereby in case of trouble. The stations are synchronized at sub-stations, which are 100 to 150 miles from any power station.

We have now adopted the type shown in Fig. 6, two-break switches for the ordinary station, and four-break in each tank for the heavy service. These switches are grouped in three-pole arrangement as shown in Fig. 7.

For small sub-stations, for line-sectionalizing switches, and for disconnecting from bus-bars, switches of the type shown in Figs. 8 to 11 are used. In handling the high-tension lines, these switches are used as much as the oil-switches.

A glance at Fig. 12 will show that our high-tension lines are also practically distributing lines, as loads are taken off at a great many points. We have more than 100 sub-stations on our lines. Such a system is, of course, much more difficult to operate than a straight away line with a power station at one end and a load at the other.

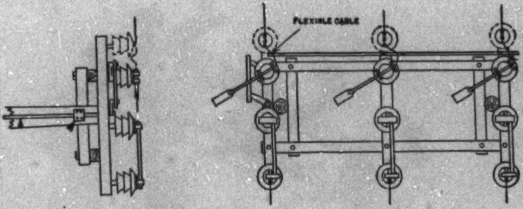


FIG. 10—Outdoor switch and fuse for small sub-stations.

On the hydraulic construction and also on the power-house and sub-station installation and construction, the engineer is required to devise something that will pay the largest net income in a given number of years. Sometimes he is called upon to make installations on the assumption that the plant is to be abandoned in a few years. Of course, the engineer will be criticized if he puts in a plant to meet present or apparent future needs and, due to some change in the industry or development of the country, the plant must be remodeled later. But it is the business of the engineer to solve his problems as he sees them.

I have given these examples of line and switch construction to show that *the best solution of a problem may be one which accomplishes the purpose satisfactorily with the least amount of money*, on account of the changes in design which become apparent as our experience is broadened and as the industry develops. That there will be further advances is certain, but, as far as high-tension work is concerned, little of the present apparatus—transformers, insulators, switches—need be thrown away; for, should the line voltage be forced up, the present apparatus may be used on the lower-voltage lines. And too, the high-tension transformer is so flexible in its operating-voltage connections that use can always be found for it. It is very probable that in time higher-voltage trunk lines will be built which will feed into the present lower-pressure (60,000 volts) lines at various points, using the present 60,000-volt lines for the primary distribution, and stepping down to about 11,000 for the regular factory distribution. An example of work of this kind is shown by our system. A great many miles of comparatively low-tension lines—10,000 to 23,000— have been changed to higher voltage, but all the old line

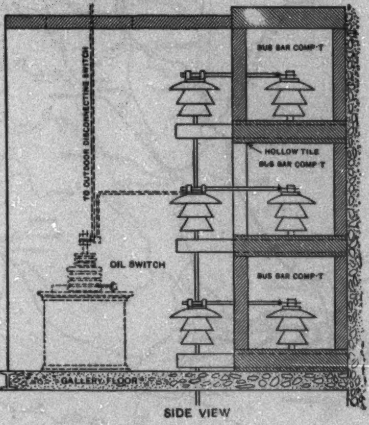
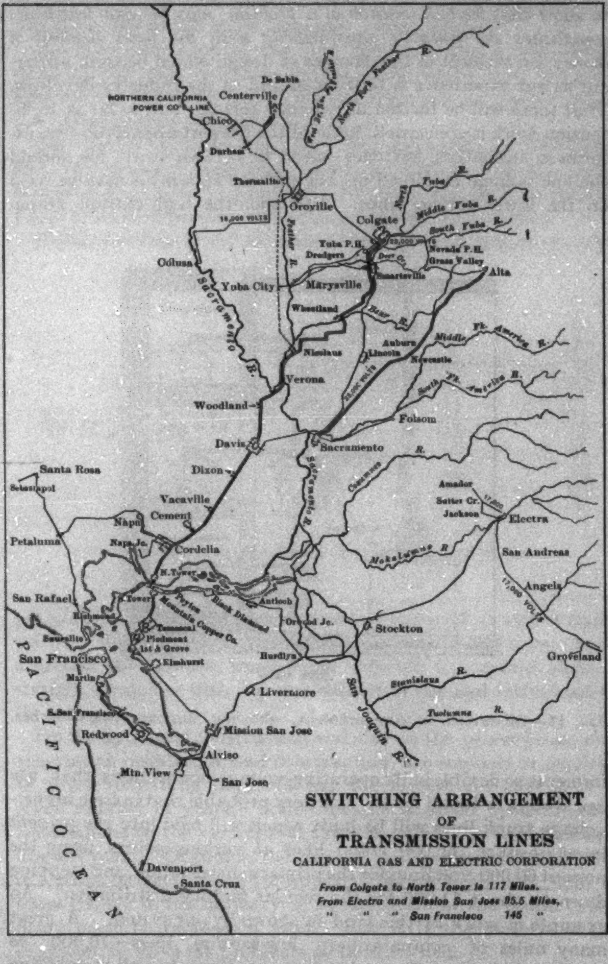


FIG. 11—Oil-switch in compartment, showing disconnecting-switches.



SWITCHING ARRANGEMENT
OF
TRANSMISSION LINES
CALIFORNIA GAS AND ELECTRIC CORPORATION

From Colgate to North Tower is 117 Miles.
From Electra and Mission San Jose 95.5 Miles,
" " " San Francisco 145 "

De Sabla
NORTHERN CALIFORNIA POWER CO. LINE
Centerville
Chico
Durham
Thermalito
West Br. No. Fk. Feather R.
North Fork Feather R.
Oroville
16,000 VOLTS
Feather R.
North Yuba R.
Middle Yuba R.
South Yuba R.
Colgate
Yuba P.H.
Dredgers
22,000 VOLTS
Nevada P.H.
Deer Cr.
Grass Valley
Smartsville
Alta
Colusa
Sacramento R.
Yuba City
Marysville
Wheatland
Bear R.
Auburn
Lincoln
Middle Fk. American R.
Newcastle
Nicolaus
Verona
22,000 VOLTS
South Fk. American R.
Woodland
Folsom
Davis
Sacramento
Dixon
Cosumnes R.
Sacramento R.
Santa Rosa
Sebastopol
Vacaville
Amador
Sutter Cr.
Jackson
17,000
Electra
Cement
Napa
Petaluma
Napa Jc.
Cordelia
San Andreas
Mokelumne R.
N. Tower
Angels
17,000 VOLTS
San Rafael
S. Tower
Peyton
Black Diamond
Antioch
Richmond
Mountain Copper Co.
Oxnard Jc.
Stockton
Sausalito
Temescal
Piedmont
1st & Grove
San Francisco
Elmhurst
Hurdlys
Groveland
Martin
Livermore
Stanislaus R.
PACIFIC OCEAN
San Joaquin R.
Tuolumne R.
S. San Francisco
Redwood
Mission San Jose
Alviso
Mtn. View
San Jose
Davenport
Santa Cruz

FIG 12.—All lines not otherwise marked are at 60,000 volts.

material, switches, insulators, transformers, etc., have been again utilized.

The saving in conducting capacity and the improvement in the service and the salvage have well paid for all the changes. No doubt a part of the future work of the electrical engineer will be to redesign and reconstruct the high-tension systems for the economies to be gained. The ease by which the change to the higher voltage may be made as necessity arises is encouraging alike to the transmission engineer and to the investor.

DISCUSSION ON "SOME POWER TRANSMISSION ECONOMICS", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

Chas. P. Steinmetz. This paper describes a construction suitable for power transmission where the utmost reliability is not necessary, but where cheapness is needed to make the installation feasible. It is desirable in all such discussions to give some clue of what is understood by "reliable" or "satisfactory" operation. In listening to statements of satisfactory operation of transmission lines, it will be found that "satisfactory operation" is a flexible expression; for what may seem to one engineer under certain conditions as satisfactory, may to another engineer, seem very unsatisfactory. For instance, the chief engineer of a large city told me a few days ago that in his city the power has not been off the low-tension bus-bar in fifteen years. In such a case a number of shutdowns averaging one shutdown per year, of five minutes or less duration, would be unsatisfactory operation; because if it should happen there probably would immediately be a legislative committee to investigate why it happened that some thousands of citizens were caught by the failure of the power in elevators midway between the floors of office buildings. In another instance, in a transmission line supplying power to a mining district, it may be perfectly satisfactory operation if the number of shutdowns averages not more than two per month, with perhaps a total duration of an average of twenty minutes per month. That may be perfectly satisfactory in that case.

It would seem desirable, then, for an engineer who makes a statement of this kind to preface his statement with something like this: I consider as the limits of a satisfactory operation a number of shutdowns averaging not more than two per month of a total duration of not more than twenty minutes per month; or I consider as the limits of satisfactory operation a number of shutdowns averaging not more than two per year of a total duration of not more than five minutes per year, whichever may be the case. Then we really could compare the cases intelligently, while now we really cannot do so.

The thing which brought this matter to my attention is that we have had so much discussion of what is proper to do for transmission at voltages above 60,000, and we have discussed transmission lines of 100,000 volts, and more than 100,000 volts, and, too, someone has asked the question, which has remained unanswered, whether there is anywhere in this country or anywhere else any transmission system in successful satisfactory commercial operation of 60,000 volts or more. The answer to the question would entirely depend on what one calls satisfactory operation. If satisfactory operation is to be judged from the experience of the city engineer in whose system the power had not been off the bus-bars for fifteen years, I do not think there is any such system, or will be for a long time. If by satisfactory operation is meant the case of the engineer who figures the time when the power is off the circuit in per cent. of the total time, and is satisfied if it is not more than one per cent. of the total time when there is no power, then there will be quite a number of systems in successful operation.

F. B. H. Paine: I think that Mr. Steinmetz asks too much of the engineer. I was brought up in a school where the use of the word "satisfactory" was prohibited. Manufacturing companies have eliminated that word from their vocabularies and so I think it would be necessary to understand, not so much what the engineer of the transmission company thought was satisfactory, as what each one of his patrons thought was satisfactory; I have yet to find a unanimity of opinion anywhere as to what satisfactory service may be.

The great value of Mr. Baum's paper is in bringing out strongly the great difference in transmission practice of the West and the East. I have recently made an extended trip in the West in order to harmonize, if I could, the conflicting statements as to the availability of certain apparatus and methods for high-voltage transmission that are not regarded in this part of the country as permissible, yet I knew to have been in successful operation in the West. The most striking differences which Mr. Baum brings out in his paper are two: the use of the ground as a return for high voltages, and the fact not expressly stated in his paper, that no automatic apparatus is used on their system. The fact that no automatic apparatus is used permits the use of a class of switching and other line apparatus, even on a system of that magnitude, which would be utterly impracticable on a system of lesser magnitude where automatic apparatus is used. The oil-switches that are shown here are excellently constructed, but to one who is accustomed to the immense switches used for 60,000-volt service in the East they are astonishing; they only cost $200 or $300, and we are accustomed to pay $1500 to for our switches. I attribute the successful use of these cheaper well-made switches to the fact that they are non-automatic and are used only under more or less ordinary operating conditions, not emergency conditions. They are used, furthermore, on long transmission lines with comparatively small conductors and the most complex system that is imaginable. They are extremely useful devices; they ought to be available for special service in the East, but they would not do to control large transmission systems with large conductors and large generating units behind them.

The use of the ground as a conductor I have supposed to be open to serious objections. I should suppose this to be the case particularly, as in their case, where it is used for 60,000 volts, for 12,000 volts, and 2300 volts and how many other voltages I do not know, I wish that Mr. Steinmetz and Mr. Scott would speak on that phase of the subject.

There are a good many things described in the paper that indicate a construction applicable only to a country free from extremely high winds and sleet. The very ingenious pole-line construction would not be usable in such a climate as New York, and this should be fully appreciated. Mr. Baum regards two independent pole lines entering the city from different directions as being more reliable than two circuits on an individual tower line, or two circuits each on their own tower lines, presumably supplying power from the same source. The difficulty in building up one circuit out of two, two wires on one, and one on the other line is very much increased and made almost impracticable if the circuits themselves are distant from each other and if each line feeds different customers. Lines in the same vicinity are equally likely to injury from lightning whether they are adjacent or two or three miles apart.

The reason for the use of different tensions in the three wires on a pole line is not obvious, and I was not able while in the West to ascertain any satisfactory reason for the practice. Unbalanced strains on one fragile structure are mechanically very undesirable.

The reason given by those in charge of various lines was that it was found impossible to string the wires sufficiently close to the same tension, therefore in a wind storm the different periodicity of the swing of three wires would ultimately bring them together. I think a more careful inspection of the lines during construction would make it possible to string them to the same tension. On our 400 miles of line no one has ever discovered a tendency of the cables to swing together. We use a seven-foot triangle, with spans normally at 550 feet and ranging up to 1200 feet, 1200 feet being approximately the longest span we have. We find the cables swing synchronously and are sluggish in their movement when subject to sudden gusts of wind.

A paper presented at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 28, 1907

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SINGLE-PHASE HIGH-TENSION POWER TRANSMISSION.

BY E. J. YOUNG.

The recent advance in Europe of the Thury direct-current system of power transmission demonstrates the fact that unless an alternating-current system approaching it in simplicity of design and economy of material is developed, it is only a question of time before the high-tension direct current will gain a hold upon this continent. Consequently, the writer proposes a high-tension single-phase system having several desirable features not in common with either the direct-current or the three-phase system.

While the present three-phase system is more flexible than the direct current, it is more complicated, and requires a considerably greater outlay for transmission material. The ordinary single-phase system is simpler than either of these two, but requires 25% more copper than the three-phase system and a proportionately greater amount than direct current. Then again, considering the strain upon the insulators as a standard of comparison, the fundamental difference between direct- and alternating-current systems gives the former an advantage that no alternating-current system can overcome.

In Fig. 1 is shown a general outline of the proposed single-phase system. Single-phase generating apparatus is supplying energy to step-up transformers—for convenience only one is indicated.

The center of the high-tension windings is permanently grounded, thereby reducing the electromotive force from line to ground to one-half that between the line wires, and in so doing placing single-phase transmission at least on a par with three phase in the matter of economy of copper. At the receiving end the step-down apparatus is similar to that at the power station, the center of all high-tension windings being grounded. At the sub-station, there is a motor-generator set consisting of a single-phase synchronous motor and a three-phase power and lighting generator. The set is started by an ordinary single-phase series motor operated by current from an autotransformer connected across the secondaries of the step-down transformers. The exciter may be on the motor-generator shaft as in Fig. 1, or operated by a separate motor, as best suits the conditions.

An example will probably serve to illustrate the comparison between the different systems, especially those by alternating current. Therefore it is proposed to transmit 15,000 kw., 100 miles with 10% loss. The electromotive force to be 50 kilovolts from line to ground at the receiving end, and the alternating-current frequency to be 30 cycles. The following conditions for the three-phase line are assumed:

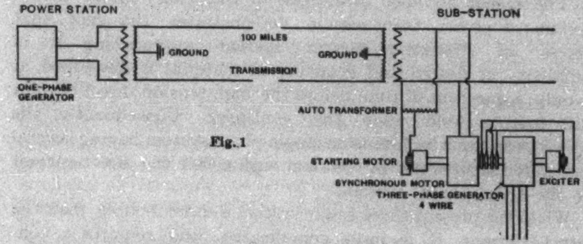
POWER STATION
SUB-STATION
100 MILES
GROUND
GROUND
TRANSMISSION
ONE-PHASE GENERATOR
AUTO TRANSFORMER
STARTING MOTOR
SYNCHRONOUS MOTOR
THREE-PHASE GENERATOR 4 WIRE
EXCITER

Fig. 1

Power-factor = 0.9.
Star-connected transformers with grounded neutral.
Electromotive force to ground = 50 kilovolts.
Electromotive force across line = 50×1.732 kilovolts.
By transmission formulas the copper section per line will be:

$$1. \qquad \text{Cir. mils} = \frac{D \times P \times K}{M \times E^2} \text{ in which}$$

D = 100×5280×1.02 ft., 2% allowed for sag in conductors, etc.
P = 15,000,000 watts.
K = 1330 for 0.9 power-factor, three phase.
M = 10% loss.
E = 50×1.732 kilovolts.

Consequently:

$$2.\quad \text{Cir. mils} = \frac{100 \times 5280 \times 1.02 \times 15{,}000{,}000 \times 1330}{10 \times (50{,}000 \times 1.732)^2} = 143{,}270.$$

$$\text{Weight of copper per mile of line} = \frac{143{,}270 \times 3}{62.5} = 6876 \text{ lb.}$$

As shown in Fig. 1, the center of the high-tension windings is grounded. The electromotive force of the single-phase system may therefore be double that to ground and still retain the same strain upon the insulators as in the three-phase system. One-phase conditions:

Electromotive force..........100 kilovolts.
Power-factor........0.9
Constant *K*........2660 for 0.9 power-factor, single phase.

Therefore:

$$3.\ \text{Cir. mils} = \frac{100 \times 5280 \times 1.02 \times 15{,}000{,}000 \times 2660}{10 \times 100{,}000^2} = 214{,}890.$$

$$\text{Weight of copper per mile of line} = \frac{214{,}890 \times 2}{62.5} = 6876 \text{ lb.}$$

In order that the direct-current system shall be under the same conditions as the alternating current, the electromotive force to ground will be 50 ÷ 0.707 or approximately 70.7 kilovolts. This will give practically the same strain on the insulators as would 50 kilovolts alternating current. By grounding the row of generators at the power and receiving stations, as proposed on the direct-current transmission from Monthoux to Paris, France, there would be a potential of 141.4 kilovolts between line wires.

According to formula 3, with K equal to 2160 for direct-current, all other factors remaining the same, we obtain:

$$4.\ \text{Cir. mils} = \frac{100 \times 5280 \times 1.02 \times 15{,}000{,}000 \times 2160}{10 \times 141{,}400^2} = 87{,}270.$$

$$\text{Weight of copper per mile of line} = \frac{87{,}270 \times 2}{62.5} = 2792 \text{ lb.}$$

Comparing these results, we find that as far as transmission material is concerned the direct-current system is far more economical than either the three-phase or the single-phase system.

There is practically no choice between the latter two. Therefore, any advantage the alternating-current system may have, must necessarily be in the power house and the sub-station.

Comparing now the three phase and single phase with the idea of estimating the probable saving the latter would represent in line material: on the single-phase system there would be at least 12 less insulators and pins per mile if steel towers were used, and 44 on ordinary pole construction. At $2.50 per pin and insulator, this would mean an initial saving of $30, or $110 a mile for pins and insulators alone. The cross-arms, etc. of the single-phase line would probably be longer and heavier than those of the three-phase line on account of the wires being farther apart, due to higher electromotive force, but this is more than compensated for by the poles being about 5 ft. shorter, since the upper wire is done away with. There is also the difference in cost in stringing wires—three wires on one system and only two on the other.

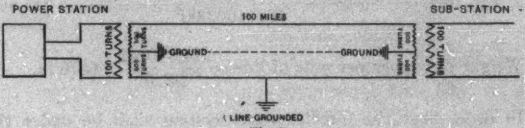

Fig. 2

One of the most important advantages of the proposed system, with reference to continuity of service in case of trouble on transmission line, is shown in Figs. 2, 3, and 4. In Fig. 2 the line is supposed to be grounded. The number of turns in the transformer windings is indicated in order to illustrate the effect of such an occurrence. With independent automatic circuit-breakers in each high-tension line at the power house and sub-stations—those at the power house operated by overload time-limit relays, and the sub-stations supplied with reverse-current relays operating with practically no time-limit—the affected line will be cleared by the short-circuit.

We have now a 50-kilovolt transmission in which the ground serves as one conductor. At the receiving end the ratio of transformation is doubled, but at the same time the electromotive force is reduced one-half. Consequently, the secondary potential will not be altered by one line being cut out of circuit on account of trouble or for repairs and inspection. In order to raise the system to approximately its original capacity, the high-tension windings, being in two sections, are connected as in Fig. 3.

Upon removing the trouble and connecting the transformers as in Figs. 1 and 2 it would appear that, by simply closing the switches upon the repaired line, normal operating conditions would be resumed. Although this last operation might result in conditions that could only be learned by experience, the illustration will show that as long as one line remains upon the insulators the service will neither be interrupted nor the transmitting power of the line very much reduced. In the event of the above trouble occurring upon the three-phase or direct-current lines, the effect is different. With three phase the entire system will be interrupted; with direct current one half the motor-generators will stop. It will therefore be seen that the necessity of a duplicate line is much less needed on one phase than on either of the other systems.

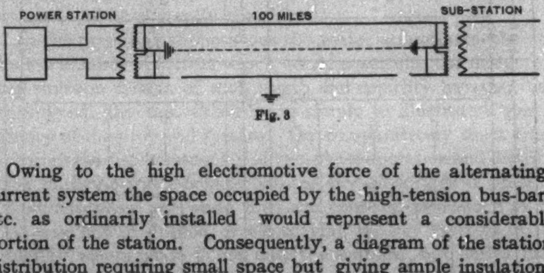

Fig. 3

Owing to the high electromotive force of the alternating-current system the space occupied by the high-tension bus-bars etc. as ordinarily installed would represent a considerable portion of the station. Consequently, a diagram of the station distribution requiring small space but giving ample insulation, the high-tension lines being under oil, is shown in Fig. 4; although applicable to three-phase or single-phase, it will obviously present less complications when used with the latter.

In Fig 4 are shown four independent transformer units placed in a single case partioned into four chambers. Each chamber contains a transformer, the switches necessary for its operation, and the interconnecting bus-bars between adjacent transformers. The lines *C* and *D* lead to low-tension generator bus-bars; *A* and *B* lead to high-tension line-switches which are controlled by overload relays; four lines, that is, *A* and *B*, being necessary in order to facilitate inspection or repairs of individual transformers while others are in operation. It will be seen that any transformer may be cut out of circuit from adjacent units by the disconnecting switches S, which, under normal operating conditions are all closed; S_1 and S_2 indicate double-pole, double-throw, remote-control switches for connecting the high-tension coils either in series across A and B, or, in the event of trouble on one line, in parallel from ground G to the unaffected line.

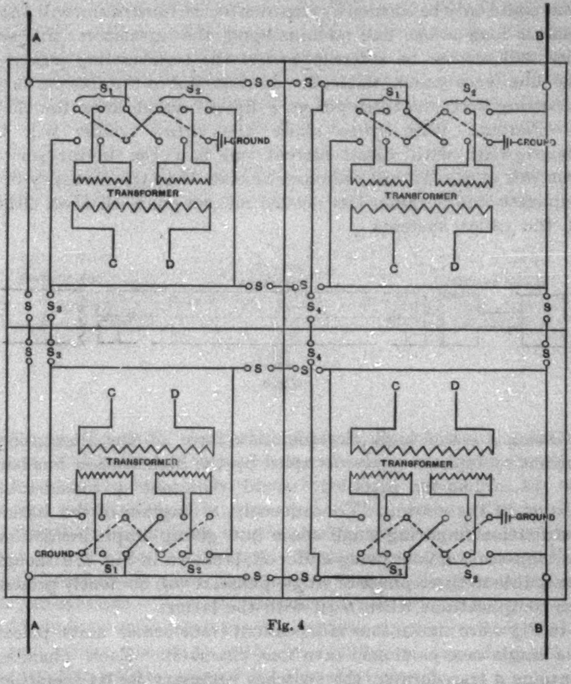

Fig. 4

The interconnecting switches S_3 and S_4 connect the bus-bars in different chambers. Under ordinary operating conditions all transformer switches S_1 and S_2 would be thrown to the right, thus putting the high-tension windings in series. In the event of line A being cut out, all switches, S_1, could be thrown to the left there by placing the two windings in multiple from B to ground G;

if line *B* is disconnected, all switches, S^1, would be to the right and S_2 to the left. Since the cooling coils have been dispensed with, the intention is to place the entire case in a pit surrounded with running water, or to have the oil withdrawn from the case and cooled externally, as is proposed in certain transmission plants.

Notwithstanding all that has been said in favor of the single-phase system it has several disadvantages. In the first place the generating apparatus costs more than three-phase, but less than direct-current apparatus. The inability of operating large induction motors is also a serious disadvantage, and would necessitate the use of motor-generators in many cases. Then again, there might be greater liability of surges in the single-phase circuit due to the larger current carried by them, but the troubles accompanying star-connected transformers, as explained by Mr. J. S. Peck, are entirely eliminated. The number of transformers upon the system, as shown in Fig. 4, will be much less with single phase, and the entire switching apparatus is not only reduced but also greatly simplified.

In the preceding suppositions the writer appreciates the fact that a number of factors which would enter into the design of a transmission system of such length and capacity have not been considered, the case taken being simply to illustrate a general theory of the proposed system. On comparatively short transmissions the disadvantages of single-phase operation and distribution would no doubt counterbalance any advantage it presents. However, where very long lines are contemplated, such as the 250-mile line in France, or electrifying railway systems in this country, single phase is not only the simplest, but unites maximum reliability of service with a minimum number of transmission wires.

DISCUSSION ON "SINGLE-PHASE HIGH-TENSION POWER TRANSMISSION", AT NIAGARA FALLS, N. Y., JUNE 28, 1907

Chas. P. Steinmetz: In this paper Mr. Young gives a discussion of the relative economies of the different transmission systems. In bygone years considerable discussion took place on this point, and it was shown that the three-phase system requires only 75 per cent. of the copper of a single-phase system or a four-wire two-phase system, on the basis of equal maximum electrostatic stress. With the change of industrial conditions, such conclusions will have to be revised. When the matter was discussed before, then the statements were correct, because in those early days all electrical circuits were operated as isolated systems without grounded neutral; and in that case the voltage which came into consideration was the voltage from conductor to conductor, across two insulators, and in that case the three-phase system has an advantage of 25 per cent. in copper.

Now, with voltages of 60,000 or more, it is almost always the custom to ground the neutral, and in this case the maximum stress is from the conductor over a single insulator to ground, corresponding to the voltage which in the single-phase system is the voltage between the conductors divided by two, or half the line voltage. In the three-phase system the voltage between the conductors is divided by $\sqrt{3}$ or the Y, voltage; in other words, when operating with grounded neutral, all systems, single-phase, two-phase, or three-phase are exactly alike in their copper economy. They are all combinations or multiples of single-phase systems with grounded return and zero resistance in the return. All these systems, as we know, theoretically can be considered and are considered as a number of single-phase systems, each system being one of the transmission wires, returned over the ground with zero resistance in the ground. The statement that the three-phase system has an economy in copper of 25 per cent. is not correct for the high potential line with grounded neutral, for at present with grounded neutral the three-phase system does not offer any advantage in copper economy over the single-phase or four-wire two-phase system. The advantage of the polyphase system over the single-phase system is only the greater usefulness of polyphase power, since the largest part of the power is always used for synchronous motors, induction motors, synchronous converters, etc. The advantage of the three-phase system over the two-phase system is the advantage of three wires over four wires. This is what upholds the three-phase system at present.

In comparing the three-phase or single-phase system with direct-current high-tension transmission, it was pointed out in the early days that they cannot be compared as regards copper economy, on the basis of maximum voltage or effective voltage, because one stress is alternating with the average equaling zero, the other stress is unidirectional, and so all those effects of the electrical stress which are unidirectional exist to a very small extent only in the alternating-current system, while prominent in the direct-current system, and all those effects which depend on instantaneous voltage are greater in the alternating-current system. So direct-current high-tension and alternating-current high-tension cannot directly be compared on the basis of some voltage, average, effective, maximum, or whatever it may be. but require a further investigation which the future will give; and the future will indicate whether the direct-current high-potential transmission should be reintroduced to any appreciable extent. I do not believe it will.

E. H. Schwarz: It is obvious that in single-phase transmission, single-phase alternators might be used, and I would like to know, where there is a low power-factor due to a heavy overload, whether the armature reaction in a single-phase machine knocks down the voltage less than in a three-phase machine?

Chas. P. Steinmetz: The opposite is the case. In a single-phase machine the armature reaction lowers the voltage more at heavy load and low power-factor than in the polyphase machine, and not only lowers the voltage but also changes the wave shape by superimposing the triple harmonic on the main wave. The result is that a machine cannot be operated at the same output single-phase that it can be operated polyphase; that is, a certain type and size of machine when built single-phase must be rated at the lower output, probably about three-quarters of that when built as a polyphase machine.

E. H. Schwarz: In making short-circuit tests on three-phase and single-phase machines, I have noticed that it takes less field current in single than in three-phase. I thought that was due to the fact that in the three-phase alternator the maximum current in one phase would demagnetize the field at a time when the other phases should be generating a certain voltage, while in the single-phase alternator the demagnetization due to maximum current could only affect the one phase of the machine, and since the voltage would be zero at this time, the demagnetization would have no effect upon it.

Chas. P. Steinmetz: If there is a three-phase machine and it is short-circuited single-phase, it will require less excitation for the same short-circuit current as when short-circuiting the machine polyphase. But the same current in the single-phase machine corresponds to less power, since for the same power the single-phase current should be $\sqrt{3}$ times the three-phase current; while with the same current the field excitation and the regulation may be better single-phase, with the same power; that is, $\sqrt{3}$ times as much single-phase as three-phase current. The regulation single-phase must be very much poorer than three-phase; in other words, at equal output, other things being the same, the single-phase machine gives poorer regulation and also a greater heating than the three-phase machine. Inversely, to get approximately the same regulation and heating in a single-phase machine, the output has to be reduced considerably below that which the same machine would have as a polyphase machine.

C. T. Wilkinson (by letter): The feeling aroused not only in Europe but also in this country in regard to the high-tension direct-current system of transmission devised by Mr. Thury is illustrated by Mr. Young's interesting paper. As one who has observed somewhat carefully the operation of this system I beg to offer the following comments.

First, and possibly the most important consideration, is telephonic and telegraphic disturbances, due to the grounding proposed by Mr. Young. Where this one-phase system operates under normal conditions it is uncertain whether serious trouble of this character will develop, but it seems highly probable that when running under the emergency condition proposed by Mr. Young in a case of a breakdown of one line that very serious difficulty would be expected.

The connection of the two high-tension transformer windings in multiple, as shown in Fig. 3, doubles the current of the transmission line and therefore increases the losses four times while it is possible that regulation would be seriously interfered with and that considerable trouble might be experienced due to hunting or surging of the single-phase synchronous motor-generator sets at the receiving end.

In the case of a ground on the direct-current system, Mr. Young states that one-half the motor generators will stop. In this connection attention may be drawn to the method of building the Thury sets in semi-groups, each semi-group containing two armatures on the same shaft which are connected in series, the idea being that, if the station capacity is to be increased at any time, it can be done by connecting these two armatures in multiple, thus doubling the current and halving the voltage. While, of course, the switching arrangements should enable this to be done rapidly in case of breakdown, this would somewhat reduce the present remarkable simplicity of the Thury system. This method would solve the difficulty quite satisfactorily, though of course the line losses would be doubled. The semi-groups being thus connected in multiple, they would all be thrown across between the earth and the remaining line.

Perhaps, it is worth while considering the arrangement Mr. Thury has devised in case a breakdown occurs where it is not desirable to ground the whole line. In these cases he places the transmission line (as in the case of the transmission from Moutiers to Lyon) in several sections, providing what are called "earthing-cabins" at intervals in order that only the broken section of the line need be earthed.

With regard to Fig. 4, it seems at first sight as though greater simplicity ought to be obtained, since a large number of high-tension large rupture capacity switches must be employed. Further, it is not quite clear why four transformer tanks must be used; would not two separate tanks be ample with a third in reserve? Possibly Mr. Young would be kind enough to explain this matter a little more fully.

When comparing this system with the direct-current system it must be remembered that it is a comparatively easy matter to guard the latter system from lightning trouble; for in spite of the high advance made in all types of lightning arresters in recent years, trouble is occasionally experienced with alternating-current transmission.

The further troubles due to capacity and inductance need only be referred to, since it is, of course, thoroughly appreciated that their absence is an inherent advantage of the direct-current system. It might be well, however, to hold in mind that with high voltages the direct-current system allows the line wires to be somewhat closer together with resulting economy in transmission towers.

G. T. Fielding Jr. (by letter): While engineering practice sometimes drifts in the wrong direction, it seems as though there are legitimate reasons for abandonment of the original single-phase machinery and systems, passing of the quarter phase, and then gradually but surely settling down to three phase.

Engineers and station operators have not a very friendly feeling toward single-phase machinery, especially in units of appreciable capacity. The heavy vibration under load, the excessively large exciting current with inductive loads, and inferior regulation do not add in its favor. The most serious drawback to the single-phase synchronous motor is the lack of starting torque, and with units of large size difficulties in bringing up the speed and synchronizing in are anticipated.

A single-phase motor caused to drop out of step by momentary overload or any passing cause cannot of itself regain its synchronism as can a three-phase machine, but will quickly come to rest.

The cost of a single-phase machine would probably be about 20% more than a three-phase type if figured on an all around equal basis.

Though it is said that the switching would be simpler with the single-phase system, it is not evident from the writer's layout in Fig. 4. It would seem that the half transformer might be arranged to connect in series rather than in multiple in case of the failure of one line. The amount of power transmitted upon the same basis could not be doubled by making the multiple connection, and if the line insulators were based on a liberal safety-factor the series combination should reasonably be maintained until repairs are made on the damaged line.

While Mr. Young calls to attention some interesting points in making comparisons, it would seem that the disadvantages of single-phase machinery would weigh heavily upon whatever merits there may be in the transmission.

A paper presented at the 221st Meeting of the American Institute of Electrical Engineers, New York, Oct. 11, 1907.

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THE GROUNDED NEUTRAL, WITH AND WITHOUT SERIES RESISTANCE, IN HIGH-TENSION SYSTEMS

BY PAUL M. LINCOLN

The object of this paper is to raise for discussion the question of grounding the neutral, a question that continually confronts the engineer operating an alternating-current generating, transmitting, or distributing system. The writer wishes to consider this question from the viewpoint of the operating engineer, since it is naturally he who is most interested.

The questions that would arise in the mind of the operating engineer are probably these:

1. Why should the neutral be grounded? What advantage would be gained, if any? and what disadvantages would be encountered?
2. If a ground is used, shall it be at one point of the system, or several?
3. Shall a resistance be used between the neutral and the ground? and if grounded at several points, shall a resistance be used in each place?
4. If a resistance is used, how much? and what shall be its current-carrying capacity?
5. What character of resistance is best?

Let us begin at the beginning of this list of questions and itemize, so far as possible, the advantages and disadvantages of a grounded neutral. The first part of this discussion will deal with the general question of ground versus no ground. Later in this discussion the modifications introduced into this general question by use of resistances, multiple grounds, etc., will be briefly treated.

Advantages. *a.* Electromotive force between conductor and ground remains fixed and constant.

b. Prevents abnormal static induction on neighboring circuits.

c. Provides opportunity for using the ground as a working conductor.

d. Makes possible the detection (and immediate removal if desired) of any grounded portion of the system.

e. Insures equality in the condenser current drawn from each phase.

Disadvantages. *f.* One ground disables a part or the whole of the system.

g. A proper ground is difficult to obtain.

Discussing more in detail these points of advantage and disadvantage, we find:

Advantages. *a.* In practically every transmission system the greatest danger of breakdown of insulation exists between line and ground, rather than between lines; it is therefore highly important that the voltage from line to ground be permitted to assume no abnormal or excessive value. The higher the line voltage the greater becomes the importance of this point, since the factor of safety of insulation naturally decreases with increasing line voltage. With the neutral fixed at ground potential, it is impossible to obtain, between any conductor and the ground, more than a certain definite proportion of the maximum line voltage. In a three-phase system—including as it does practically all transmitting and distributing systems—the voltage between the neutral and ground is about 58% of that between conductors. If, therefore, the neutral be connected permanently and solidly to ground, the maximum potential that can develop between the line and ground is about 58% of the voltage between the conductors. With an ungrounded system a ground on one conductor will cause full line potential to develop between the two remaining conductors and ground.

On further analysis it is doubtful if all the advantage apparent at first sight is really obtained, for it can safely be asserted that in the large majority of cases it is not the action of the steady line voltage that causes breakdowns in the insulation of transmitting or distributing systems; the voltage strain necessary to cause breaks in insulation is usually very much higher than the normal voltage applied, even in the case where a system is operating with one conductor grounded. The condition giving rise to trouble is to have superimposed upon the normal line voltage a so-called "surge" of such value that, when added to the normal strain, their resultant causes sufficient strain on the insulation to break it down. Lightning is the usual cause of surges, although they may be caused by many other things; for instance, by switching, or a partial ground, or a broken conductor, or a heavy short-circuit. Insulation being once broken down, the normal voltage is usually sufficient to maintain an abnormal flow of current through the break. With the neutral grounded, a momentary break in insulation at one point on one conductor gives rise to opportunity for a destructive arc at that point. With the neutral ungrounded, before a destructive arc can take place there must be simultaneous breaks on the insulation of two separate conductors. The use of a resistance between the ground and neutral modifies these conditions, as will be discussed in a later paragraph.

A very material advantage incident to this fixing definitely the maximum potential of conductors above ground is that it allows a much closer adjustment of lightning-arresters than would otherwise obtain; that is, the arresters can be adjusted so that a comparatively small rise above normal potential to ground will discharge across them. In an ungrounded transmission system it is not safe to adjust for a discharge potential materially less than line voltage; otherwise, in the event of one conductor becoming grounded, the constant discharge which necessarily occurs over the lightning-arresters between the two good conductors and ground will destroy the arresters within a short time.

b. An advantage incident to keeping the neutral of a transmission system at ground potential is to prevent abnormally large static induction by a transmission line on neighboring circuits. Those who have endeavored to operate a telephone line in proximity to a transmission line will realize the importance of this point. It is evident, without further explanation, that so long as the neutral of a transmission line is at ground potential its static influence on neighboring circuits is practically negligible. If, however, one of the conductors of the line is grounded, the static induction of the remaining two is usually sufficient to prevent the satisfactory use of telephone circuits strung on the same right-of-way. Grounding the neutral will prevent such a condition.

As to electromagnetic induction, it is evident that the grounded neutral can have no influence unless the ground is carrying current. In that event, electromagnetic induction on neighboring circuits is increased. This increase is due to the fact that the return circuit through the ground, instead of being in close proximity to the outgoing circuits, thereby neutralizing most of its action, is at a comparatively great distance, making the inducing loop of large area and comparatively great power.

c. In a three-phase transmission system with the neutral grounded both at the generating station and at a sub-station, it is perfectly possible to continue the transmission of power with one of the conductors out of commission. In this case, if the phases remain balanced, the ground will carry a current 1.73 times that in each of the two remaining conductors. Furthermore, it is perfectly possible to continue to transmit single-phase power with only one of the three conductors remaining. In fact some transmission plants make a practice of running but a single wire to some customers using single-phase current, and but two of their three conductors to other of their customers using polyphase currents, relying in each case on the ground to act as a return conductor for the normal operating current. Still other plants make use of the ground as a working conductor only in emergency.

It must be counted as a distinct advantage in favor of the system with a grounded neutral that it makes available at any time the use of the ground as a working conductor. This does not mean that the ungrounded system cannot make the ground available, but in the latter case special switching arrangements must be provided, while in the former its action as a working conductor is practically automatic.

The practicability of using the ground as a working conductor is also dependent upon the ground resistance. This is an element that varies largely with geological formations, soil, season, moisture, parallel return circuits, and construction of ground-plate; it is therefore difficult to make any general statement covering this matter. However, there seems to have been no difficulty in using the ground as a conductor for moderate amounts of power at pressures of 20,000 volts and above.

d and *f*. With a grounded neutral, a ground on any conductor will cause a short-circuit. This fact may be regarded as an advantage or a disadvantage, depending upon circumstances, and also upon the point of view of the operator. If it is possible by use of the grounded neutral automatically to cut out the damaged conductor, and continue service to the affected part of the system over other lines, the grounded neutral may undoubtedly be regarded as an advantage. If, however, the grounding of the neutral means an interruption of service which could be avoided with an ungrounded neutral, the grounding may be justly regarded as a disadvantage. Protection of service is of great importance to the operator, and he is willing to run very considerable risks in order to give continuous service. That certain portions of his system are temporarily overloaded, or that part of his line conductors are temporarily undergoing an abnormal insulation strain to ground, is of no particular moment, so long as service is being rendered and the abnormal condition does not give rise to further trouble. When considering questions of protection of service, the use of resistance in the ground connection is at once involved; the discussion of this phase will be treated in subsequent paragraphs.

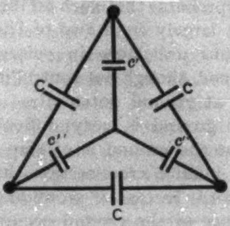

Fig. 1

e. All alternating-current transmission lines take from the generators a condenser current whose volume depends upon the size, length, and disposition of the transmitting conductors and upon the voltage and frequency supplied to them. These currents may be considered as flowing over two paths, as follows:

I. Through the condensers formed by the conductors as opposite plates, as *c* in Fig. 1, and

II. Through the condensers formed by considering the conductors as one plate and the ground as the other, as at *c'*, Fig. 1.

The currents flowing through capacity *c* are evidently independent of any grounded neutral conditions. Those flowing through capacities *c'*, however, depend entirely upon the potential of the neutral with respect to ground. With the neutral at ground potential, the condenser currents through c' are taken equally from each of the three conductors. Assuming an extreme case—one of the three conductors grounded—all the currents through c' are taken from two of the conductors, and further, the total kilovolt-amperes represented by these currents is double what it would be with the neutral at ground potential. A moment's investigation will show this latter point. With the grounded neutral the total kilovolt-amperes, taken through capacities c', may be assumed as proportional to $3\,c'\,E_1^2$, where E_1 is the potential between any conductor and the neutral. Grounding one conductor has the effect of short circuiting one of these condensers and throwing a potential of $E = \sqrt{3}\,E_1$ upon the other two. In the latter case the total kilovolt-amperes taken by condensers c' is $2\,c'\,E^2 = 6\,c'\,E_1^2$.

When the charging current is large compared with the generator capacity, it is probable that such an increase in its volume, as well as taking it largely from two of the three conductors, would cause a serious unbalance in voltage between phases. This seems to be a good, though not controlling, reason for maintaining the neutral at ground potential.

g. A satisfactory ground is very difficult to obtain. The antiquated idea that the ground is of zero resistance, because it is of practically infinite cross-section, has long since been recognized as an error. In case of grounding to a buried plate, most of the resistance of the ground occurs in the immediate neighborhood of the ground-plate, and the ground resistance depends upon the character and condition of the soil in the immediate neighborhood. This is to be expected on account of the fact that it is only in the immediate neighborhood of the ground-plate that the cross-section of the ground, considered as a conductor, is sufficiently restricted to give rise to any appreciable resistance. The conditions other than the character of the soil that make for a low-resistance ground are moisture and the exposure of a large surface of ground-plate: the larger the exposed surface the lower the resistance. It is this reason that makes water-supply systems good grounds.

Even where good engineering practice dictates a resistance in the neutral, the unavoidable resistance in the ground connection is not so valuable as it might be, because of its extreme variability. The difference of the seasons, as well as the drying-out action of any ground current that may flow, will cause large variations in ground resistance. However, on high-potential systems the presence of even the maximum amount of resistance that is contingent upon good construction is rarely sufficient to cause trouble.

MODIFICATIONS DUE TO USE OF RESISTANCE AND MULTIPLE GROUNDS

If an operating engineer has come to the conclusion that his neutral should be grounded, the next question is, naturally, that concerning the number of places to ground—whether it shall be at his power plant or plants only, or at other points where neutrals can be obtained. The answer to this question usually depends upon the object sought in grounding. If it is the use of the ground as a working conductor, there must naturally be grounds both at the generating and receiving points. On the other hand, if the object is to prevent an abnormal voltage rise on any conductor, due to the grounding of another, then the grounding of the neutral at one point is sufficient and in most cases preferable.

In some methods of connection the problem is still further complicated by the entire absence of an available neutral. In any three-phase system a delta connection of transformer or generator windings gives no opportunity of obtaining a neutral. A delta connection requires the use of a separate autotransformer connected across proper points of the delta, from the winding of which a tap may be brought out for the neutral connection. A three-phase star-connected generating system has of course the neutral at the star connection. If, however, a bank of transformers has both the primary and secondary connected in star, the star connection is not necessarily at the neutral point. In this case the neutral is practically free to move around anywhere within the three-phase triangle; in case of a dead short-circuit on any transformer, the voltage on that particular one disappears and the two remaining transformers assume the whole potential of the line, being then virtually connected in *V*. If, therefore, the star connection of a star-to-star group of transformers be connected to ground, it does not follow that the neutral is grounded; if one side is connected in delta and the other in star, then the star connection can be treated as a fixed point at the center of the three-phase triangle. In a star-to-star group proper conditions can be assured only by connecting the star point on either side to a fixed neutral; such for instance as the connection of the star of the transformers to the star point of the generating system. The star point of the generating system being fixed at neutral, this also fixes the transformers.

The question as to how many points of a system shall be grounded is naturally influenced by the above considerations. The final answer, however, must be dictated by considerations which depend upon the reason leading to making any ground connection.

Probably the most important question in connection with this whole matter of grounding the neutral is that as to the use of resistance between the neutral and ground and the amount of resistance that is best. In considering this question the following analysis is pertinent. In any polyphase system, so long as each conductor has the same capacity and ground, the same insulation from ground, and a balanced load, the neutral will remain at ground potential, whether it is connected to ground or not. In other words, so long as conditions on the transmitting or distributing system remain normal there is no occasion for grounding the neutral, as nothing will be accomplished thereby. The object sought in grounding the neutral is to take care, not of normal conditions, but abnormal ones. It is the first thought of the operating engineer to maintain his service, and he therefore installs automatic circuit-breakers and other devices to protect his system in case of an abnormal condition arising. The abnormal conditions that may arise are: 1, short-circuits; 2, open circuits; and 3, grounds.

1. *Short-circuits*. By short-circuits is meant accidental connection in any manner between conductors of opposite polarity. It is evident that under this condition the behavior of automatic devices is in no way influenced by grounding the neutral, so that the consideration of this contingency is not pertinent to this paper.

2. *Open circuits*. In a three-phase line, with the neutral grounded at both generating and receiving stations, the ground will, under normal conditions, carry no current, even though the ground be of zero resistance. If, however, one of the conductors should break, the ground immediately begins to carry current. If induction or synchronous motors are being used at the receiving end, the three-phase relation will be approximately maintained, the degree of approximation depending upon the ground resistance and upon the relative motor load to non-motor load. If the neutral is grounded at one point only, an open

circuit in one conductor would have an effect no different from that which would take place if the neutral were not grounded, except that the distribution of charging current between conductors will be somewhat disturbed and more or less of this current would pass through the ground connection.

3. *Grounds.* A ground is the most frequent abnormal condition that is encountered, and also is the one most affected by grounding the neutral. With the neutral connected direct to ground, another ground on any conductor means a short-circuit; the action of automatic circuit-breakers will then take place accordingly. The amount of current that will flow through such a short-circuit can be limited by inserting resistance, and practically the only object of resistance is to cause such a limitation of current.

The flow of excessive currents, such as would take place were there no resistance, is detrimental for several reasons. It throws an unnecessarily great strain upon the circuit-breakers which are called upon to interrupt the current. The large current flow which takes place may cause a phase distortion and drop of voltage which may, in turn, be sufficient to cause synchronous apparatus on the line to drop out of step. Almost invariably an arc takes place at the point of grounding of conductors, and an excessive current will cause excessive destruction at this point. A dead short-circuit on any system causes a heavy shock due to the tremendous currents, and a consequent tendency to distort the windings of any synchronous apparatus connected to the system.

All of these objections can be overcome to a greater or less degree by resistance in the neutral. Increased neutral resistance, however, while it limits the current flow through a grounded conductor and overcomes the above objections, can do so only by allowing an increase in the potential of the two good conductors above ground while the current flows. If the object in grounding is to prevent such an abnormal rise, the inserting of resistance tends to defeat that purpose. The choice of the proper resistance becomes a question of compromise between the disadvantages of going to either extreme. There seem to be good reasons for adopting a ground resistance which would lie between the following limits: on the one hand, large enough to prevent a severe shock to the system; or the voltage on the affected phase dropping to a point where the synchronous apparatus will drop out of step. This consideration would dictate a resistance that will not allow more than, say, three times full-load current at the most to flow through the armatures of the generators supplying the circuits. On the other hand, the resistance must be small enough to permit sufficient current to flow to trip the heaviest circuit-breaker on the system.

In all alternating-current circuits there is present a condition equivalent to a neutral grounded through a certain amount of resistance, in that static capacity exists between any conductor and ground. The longer the line and the higher the voltage and frequency, the lower the resistance in the equivalent circuit having a resistance in grounding connection. The effect of a grounded neutral, either with or without resistance, is, in case a conductor becomes grounded, to pass a current of greater or less volume through the affected conductor and into the ground. The effect of the static capacity of conductors to ground is exactly the same, the difference being that no current passes into the ground at the generating station, and that the phase relation of the current through the capacity to the electromotive force producing it are not the same in both cases. The static capacity of an overhead conductor to ground is, with ordinary line construction, from 30 to 50 per cent. greater than that between conductors. Assuming a fault that makes the affected conductor of the same potential as the ground, the affected conductor would take roughly 50 per cent. more charging current than the unaffected ones. It may be noted also that the total kilovolt-amperes of charging current in all conductors would be increased about 33 per cent. Where the normal charging current amounts to a considerable percentage of the total generating capacity, as it would in long, high-voltage, high-frequency lines, it will be seen that the condenser effect has the same action as a moderately-low ground resistance.

If a ground resistance be used, the question of its current-carrying capacity is an important one. Since current is drawn through the ground resistance only during emergencies, its capacity should be chosen to meet the maximum that any emergency can throw upon it. Usually the time during which current will flow is limited to the time required to trip a circuit-breaker, probably not more than a few seconds at most. The quantity of current that will flow as a maximum is also fixed as that which is required to trip out the most heavily set circuit-breaker. The question of current carrying capacity is therefore one which depends upon the character and setting of the safety devices used.

As to the character of resistance, permanency is the most essential. Considerable latitude is allowable in the amount of resistance, but that latitude does allow variations of many hundred per cent., such as past experience has shown is apt to take place with graphite mixtures or similar structures. A metallic resistance is satisfactory but has the objection of being expensive and bulky when the voltages involved are high. This problem has not yet been satisfactorily solved, but it seems probable that where high resistances are demanded—200 ohms or more—some form of non-metallic resistance will be found of sufficiently permanent character to be satisfactory.

In the preceding matter the writer has endeavored to present some of the considerations to be taken into account when this question of grounding the neutral arises. There are so many variables connected with this matter that it is impossible to draw any conclusion that is general in its nature. The proper action to be taken depends upon the specific conditions surrounding each individual case.

A paper presented at the 220th meeting of the American Institute of Electrical Engineers, New York, October 11, 1907.

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THE GROUNDED NEUTRAL

BY F. G. CLARK

During the consideration of the design of one high-tension installation, the question of grounding the neutral was investigated, and resulted in a decision to ground the neutral points of the generators through a limiting resistance. It was my privilege to contribute to that design and to recommend that this resistance be omitted. The reasons for grounding, the reasons for and against the resistance, and facts relatively to operation covering a period of over two years may therefore be of interest in connection with this discussion.

The installation comprises a power station centrally located for the ultimate conditions prescribed, but unfavorably to the preliminary electrification of a steam railroad requiring seven sub-stations, and undergound and overhead transmission of three-phase current at 11,000 volts and 25 cycles. Fig. 1 will give an idea of the present and ultimate conditions. The future circuits from the power station will be underground cables. There are now five 250,000-cir. mil three-phase circuits leading from the station undergound to No. 1 cable house. From there the feeders are aerial to sub-station No. 3. This will be seen to be the distributing point for the present installation. Two aerial circuits lead to sub-station No. 5. At cable-house No. 2 the circuits are submarine, and again at cable-house No. 3 submarine cables are used from the north end of the draw to the sub-station.

The feeders leading east and west from sub-station No. 3 are underground. Three circuits lead to sub-station No. 2, and from there two circuits lead to sub-station No. 1. Three circuits lead to sub-station No. 4 and are overhead from cable-house

No. 4. From No. 4 sub-station one circuit leads direct to sub-station No. 6 and another to portable station No. 1, and from there to No. 6. At portable station No. 1 a three-phase No. 2 conductor branch leads to sub-station No. 7. One circuit leads from sub-station No. 4 to portable station No. 2, and from there a single-phase No. 1 conductor circuit leads to transformer station No. 1. A typical location of this system and length of feeders is shown in Fig. 2.

The protective features are low-equivalent lightning-arresters, inverse time-element relays on circuit-breakers, a peculiar method of operating exciters, and the grounded neutral. A voltage regulator has lately been installed and has a bearing on the situation.

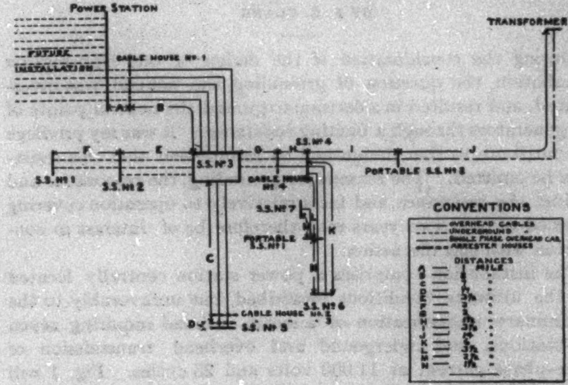
POWER STATION
FUTURE INSTALLATION
CABLE HOUSE No. 1
A
B
F
E
S.S. No 3
G
H
S.S. No 4
I
J
TRANSFORMER STA
PORTABLE S.S. No 2
S.S. No 1
S.S. No 2
CABLE HOUSE No 4
S.S. No 7
PORTABLE S.S. No 1
K
C
S.S. No 6
CABLE HOUSE No. 2
D
S.S. No 5
CONVENTIONS
OVERHEAD CABLES
UNDERGROUND "
SINGLE PHASE OVERHEAD CAB.
ARRESTER HOUSES
DISTANCES
MILE
A
B
C
D
E
F
G
H
I
J
K
L
M
N

FIG. 1

The lightning-arresters are used in connection with choke-coils at the ends of all overhead feeders. They tend to protect the undergound feeders, the station apparatus, and, to a certain extent, the aerial transmission lines from the effects of lightning and from static strains due to switching, grounds, or short-circuits. The arresters are set to discharge at 8500 volts. The pressure between the ground and two conductors of the 11,000-volt, three-phase system, with one conductor grounded, is 11,000 volts when the neutral is not grounded; it is 6380 volts when the neutral is dead grounded; it is between 6380 volts and 11,000 volts with resistance in the neutral conductor. The locations of the lightning-arresters are shown in Fig. 2.

The inverse time-element relays afford protection against overloads, and are used in connection with the oil circuit-breakers on all feeders. The speed in opening the circuit-breaker varies with the increase of current in the circuit controlled.

The relays at the power station ends of the feeders are set to allow a maximum of current to flow for a period of five seconds before they actuate the control circuits to open the circuit-breakers. This is just above the amount of current allowed as a maximum per feeder. The relays at the nearest sub-station are set to open the circuit-breakers on feeders to more remote sub-stations in four seconds for the same current. The relays in the sub-station next in progression are set for three seconds with the same current, and so on. The relays are connected with series transformers, one on each leg of the circuit controlled, to open the circuit in the event of one leg grounding.

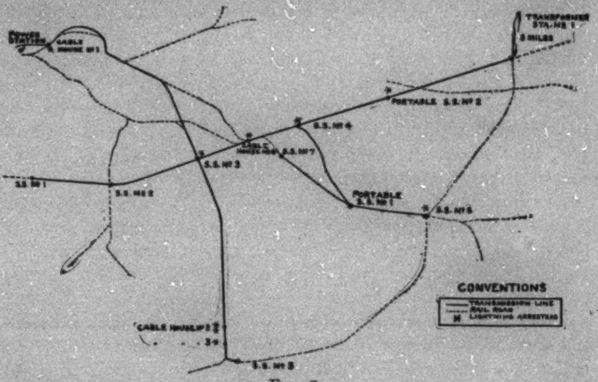
POWER STATION
CABLE HOUSE Nº 1
TRANSFORMER STA. Nº 1
8 MILES
PORTABLE S.S. Nº 2
S.S. Nº 4
CABLE HOUSE Nº
S.S. Nº 7
S.S. Nº 3
S.S. Nº 1
S.S. Nº 2
PORTABLE S.S. Nº 1
S.S. Nº 6
CABLE HOUSE Nº 2
3
S.S. Nº 8
CONVENTIONS
TRANSMISSION LINE
RAIL ROAD
LIGHTNING ARRESTERS

FIG. 2

The excitation of the generators depends upon induction motor-generators, with no steam exciter or battery reinforcement, although both are available for starting up in case of an interruption. The induction motors are supplied from the main generators through transformers and have about 2.5% slip. The output of the exciters depends upon the power-factor, which decreases with the voltage. The excitation automatically ceases whenever the bus-bar voltage goes below 5,000.

A voltage regulator tends automatically to increase or decrease the generator excitation as its voltage lowers or rises. The effect of this is to increase the intensity of the accidental overload and therefore hasten the automatic interruption. This is a radical change from the usual practice of holding up the exciter voltage under all conditions. It means a few more power station interruptions, but less damage when short-circuits occur, and less time lost in sub-stations.

The foregoing explanation of the protective features of this installation may appear to be irrelevant to a discussion of the grounded neutral, though it has a bearing which should not be overlooked. The neutral point of each generator is led to a bus-bar through a fourth pole of the generator circuit-breaker. The neutral bus-bar is connected to one end of a cast grid resistance suitably insulated. The other end of the resistance is connected to a ground-plate located in earth kept moist with salt water. There is 6.7 ohms resistance, or sufficient to allow 1000 amperes in the neutral circuit in the event of a ground. A current of 1000 amperes will raise the temperature of the resistance approximately 1000° fahr. in one minute. An ammeter on the switchboard indicates the amount of current in the neutral connection. A pilot lamp lights whenever 50 amperes or more flows through the resistance. This lamp remains lighted until an auxiliary circuit is opened, and has been instrumental in determining the number of short-circuits that were also grounds.

The grounded neutral affords protection against rises in potential and high-frequency oscillations due to grounds. An accidental ground will establish a power circuit supposedly sufficient in all cases automatically to open the circuit-breaker. Were the neutral not grounded, the accidental ground would allow the charging current to be discharged through it, tending to burn the insulation and cause a short-circuit in the case of an underground cable, or burn off the conductor in the case of an aerial line. The electrostatic charge would also tend to cause oscillations in the case of underground cables and possible breakdowns at various points of the system. This has occurred during the operation of several high-tension systems.

Grounding the neutral has the disadvantage of increasing the number of short-circuits, and consequently the interruptions of service. These short-circuits are dangerous to power-station apparatus, as they may cause breakdowns involving greater expense and loss of service than the possible resonance troubles.

There are conditions peculiar to each installation which have a bearing on this question, and these conditions determine the necessity of a resistance in the neutral circuit, the amount of resistance to be used, and whether more than one generator should be grounded.

In systems where synchronous converters have low synchronizing power, the voltage drop due to grounds will cause the converters to drop out, and a limiting resistance must be placed in the grounded neutral. In other systems the generator coils are insufficiently braced, and resistance in the neutral is a preventive for generator breakdowns. In stations where the generators are driven by slow-speed reciprocating engines the neutral points cannot be connected to a common bus-bar on account of cross-currents. A resistance would be required for each generator or that one generator be run with its neutral grounded.

A consideration of these facts led to a decision to use a resistance of 6.7 ohms in the power station of the installation described. It was anticipated that this resistance would allow sufficient current to flow through any ground which might occur to clear the system of that ground, and that grounds on two legs or short-circuits would be cleared by the inverse time-element relays, or, if very close to the power station, by an interruption of service due to the " killing " of excitation. The events of operation indicate that the neutral ground is essential and that the other protective features perform their functions suitably.

Conditions obtain, however, which mitigate against the proper operation of this protective feature. One instance will serve to illustrate this point. A wire-rigged sloop which had been anchored near the cable-house No. 2 draw (Fig. 1) drifted out of the channel until a stay-line connected with one leg of the transmission circuit, causing a ground. The ground held for about three minutes, when the boat shifted and another part of the rigging connected with a second leg, causing a short-circuit which opened the circuit-breaker. The current in the ground circuit was approximately 400 amperes, which was not sufficient to open any of the circuit-breakers between the ground and the power station. It was enough, however, to burn off an anchor chain and several of the wire stays on the boat, and to raise the temperature of the neutral resistance to that of a bright-red heat.

When the ground occurred, the neutral point rose from 0 to about 2700 volts, and the two ungrounded legs were approximately 9000 volts to ground. The electrostatic condition very nearly approached that which would obtain in an ungrounded system. The lightning-arresters being set at 8500 volts, began to discharge, and oscillations were a possibility

The inductive drop and the resistance of the ground, added to the set resistance of 6.7 ohms, were sufficient to limit the current to 400 amperes. With the 6.7-ohm resistance out, the current would have been above 650 amperes, or sufficient to have opened the nearest controlling circuit-breaker in less than one second. The inductive drop was about 1000 volts and the resistance through the ground sufficient to divert the current to the numerous telephone lines as paths of least resistance. The fact that telephone troubles are not coincident with grounds of short duration would seem to indicate that induction is not an important factor in this particular case. There have been no indications of trouble in telephone or telegraph lines due to induced potential.

Some action must be taken to prevent this ground current from causing trouble. The grounded neutral is a preventer of electrostatic troubles and therefore shoud be retained. The resistance is a positive detriment to receiving the full benefit of this effect. It should, therefore, be omitted whenever the local conditions will permit. In the case described this can be done without perceptibly increasing the hazard to apparatus. This would enable the relays to clear any of the grounds that have occurred within five seconds.

A transmission line may be so long that its total drop and the resistance of the ground will produce a condition analagous to that described. Such a case would require special treatment, as, for example, providing a low-resistance neutral conductor leading to a point safely within the area normally protected by the neutral ground at the station, and equipping the feeders to points beyond, so that they may be opened by a relay. The relay could be actuated by a small current flowing in this extension of the neutral, and in phase with current flowing in one leg of the feeder. Such a condition does not obtain on the system described and we can therefore be reasonably assured that in removing the neutral resistance we will have removed the cause of trouble incident to the grounded neutral.

During two years' operation there have been over 70 short-circuits. About 25 of these have caused sub-station interruptions, and 6 have been close enough to cause power-station interruptions. About one-half of these short-circuits showed a ground connnection. There have been 10 grounds, of which the neutral ground cleared 8. One held for four minutes and one for three minutes, both developing into two-wire short-circuits.

It is quite probable that in a system operating with underground cables only, there would be no outside disturbances in connection with sustained grounds. The lead sheaths which are generally bonded together in manholes would provide the path of least resistance for the ground circuit. The ultimate installation will require undergound cables, and except for the greater power effects, and greater charging current, will alter the present situation but little.

A paper presented at the 221st Meeting of the
American Institute of Electrical Engineers,
New York, October 11, 1907.

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EXPERIENCE WITH A GROUNDED NEUTRAL ON THE HIGH-TENSION SYSTEM OF THE INTERBOROUGH RAPID TRANSIT COMPANY

BY GEORGE I. RHODES

The chief circumstance which led to the grounding of the neutral of the Interborough Rapid Transit Company's high-tension system was the serious nature of cable burn-outs. As a rule the detectors gave indication of a ground on one leg of the system from five to thirty minutes before the circuit-breaker opened, but on account of the large number of feeders connected it was practically impossible to isolate the damaged feeder before the short-circuit occurred. In a total of twelve operating burn-outs, the grounded cable was located but twice in time to prevent trouble.

During the period between the first grounding of the cable and the final short-circuit, the system was operating under abnormal potential conditions, the two ungrounded phases operating at full delta potential of 11,000 volts above the ground. Undoubtedly the potential between phases was raised to a certain extent by the increased charging current due to unbalanced potential conditions. The presence of abnormal potentials during this period of ground was evidenced by static discharges in the power and sub-stations that could hardly be accounted for by the operation of two legs at 11,000 volts above the ground potential.

The charging current which flowed to ground through the fault before the short-circuit between phases was large enough seriously to injure the insulation of all three conductors, so that when the burn-out occurred it was so severe that the oil-switches usually opened with considerable violence. Surges were started which at times caused other burn-outs to follow, in one instance causing a very disastrous shutdown.* The cable itself was always considerably burned, all three legs being grounded and usually burned off. At times the conductors were blown apart several inches. With the faults in this condition, it was quite impossible to locate them by the bridge method, and it was necessary to open a great many manholes before locating the trouble.

In view of the fact that one phase of a cable almost invariably grounded some time before short circuiting, it was decided to ground the neutral through a resistance of proper magnitude to allow sufficient current to flow to remove the grounded feeder without affecting the system in any other way. It is obvious that with only two feeders to a sub-station, a ground on one of them will open the circuit-breakers of both, and that the certainty of continuous operation of the sub-station increases with the number of feeders.

The scheme of grounding the neutral as originally proposed was as follows: the neutral point of each generator was connected to a common or neutral bus-bar through a disconnecting switch and a current transformer. The transformer operated a relay on the main switch of the generator. The neutral bus-bar was grounded through a resistance of about six ohms in each power station, making about three ohms' resistance between the neutral of the combined system and ground. In case of a ground, the maximum possible current was 1000 amperes per rheostat, all of which was generated by the grounded generator. The relays on the feeder-switches were set to operate instantaneously at 300 amperes, and the generator relays at about 900 amperes after five seconds. Under these conditions it was to be expected that a ground on a cable would instantly remove it from service before any other disturbance could result.

The neutral rheostats were of the iron grid type having a resistance of about six ohms and a reactance at 25 cycles of about 0.3 ohms. They were made up in sixteen series sections, each insulated from the others and from the ground by porcelain insulators. Each section was made up of six series groups of cast-iron grids connected two parallel and twelve series per group. Each grid was made up of ten bars 0.25 in. by 0.75 in.

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*See paper on "High Power Surges in Electric Distribution Systems of Great Magnitude," by C. P. Steinmetz, Transactions A. I. E. E., 1905, also discussion on same.

by 6 in., and two bars 0.25 in. by 0.75 in. by 4 in. A number of extra grids were used to adjust the resistance to the required value. The rheostat will carry 1000 amperes for two minutes, a capacity far in excess of anything that would be required in service.

With the scheme as above outlined, very serious trouble was encountered from the triple-frequency cross-currents in the neutral connections. These neutral currents fluctuated very rapidly from nothing to one-half full-load current per generator.

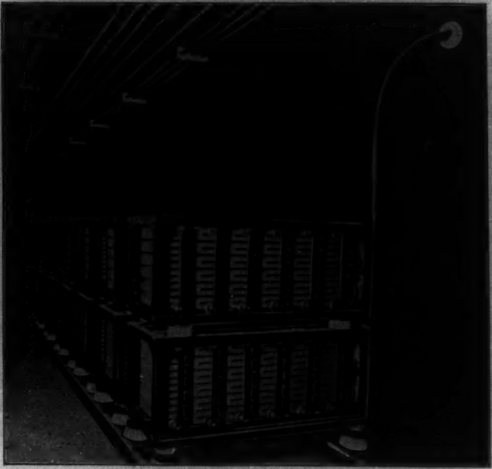

Fig 1.—Neutral rheostat.

Upon synchronizing there was a very large rush of current in the neutral, so large in fact that with four generators running it was very difficult to synchronize a fifth with its neutral grounded.* These cross-currents had such serious effects on the operation of the system that the scheme of grounding the neutral was delayed for a time to allow making some experiments.

An oscillographic study of the neutral currents was made and has been described fully.* The records (Figs. 2 and 3) proved without a doubt that the currents were caused by irregularities in the angular velocity of the prime movers and unequal excitations of the generators. It was found that the insertion of resistance in the neutral connections of the generators would reduce the currents to a safe value. This, however, was undesirable on account of the variable resistance in the ground circuit, depending on the number of generators in operation. Furthermore, resistances of sufficient magnitude and capacity would have occupied too much space to be used in these power stations.

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* "Experience with a Grounded Neutral on a High Tension Plant," C. W. Ricker, *Electric Journal*, September, 1906.

It was finally decided that full protection could be obtained by connecting but one live generator at a time to the neutral bus-bar in each power station. The transformers in the neutral connections were also disconnected from the relays on the main generator switch. Even with but one generator grounded in each power station, the interchange of current through the neutral rheostats, and the tie-line between the stations, is at times large enough to make it undesirable to open the neutral disconnecting-switch of a live generator.

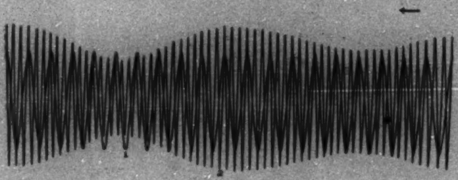

Fig. 2.—Combined effect of excitation and fluctuation of angular velocity. Curve 1, Potential between phases. Curve 2, Neutral current.

The Interborough Rapid Transit Company's system was operated for about three and one-half years without a grounded neutral, in which time about 150 miles of cable was operated for three years and 330 miles for one-half year. Since grounding the neutral, the system has been in operation for two years with about 330 miles of cable.

Previously to grounding the neutral, there were twelve distinct operating burn-outs, and since then there have been sixteen. It appears from this fact, that grounding the neutral has had no material effect on the number of burn-outs. This is as was expected.

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* "Neutral Currents of a Three-Phase Grounded System," *Electric Journal*, July, 1907.

Of the twelve burn-outs occurring previously to the grounding of the system, four shut down the power station; one other shut down two sub-stations; and four more shut down one sub-station. Of the other three which did not shut down the sub-station, two were isolated in time to prevent a short-circuit. In all of these cases, there were five or six cables to a sub-station. During most this period only the Seventy-fourth Street power station was in operation, so that there were no tie-line troubles.

Of the sixteen burn-outs that have occurred since grounding the neutral, not one has caused a shutdown of either power station; eight have shut down the sub-station fed by the cable, two have caused one other feeder to open, and six have caused no disturbance other than the opening of the switches of the feeder in trouble. In three of the cases in which the sub-station was shut down, the tie-line between the power stations opened, but without disturbing the operation of either. Of the eight burn-outs which shut down the sub-station, three were stations having three feeders each, one having four feeders, two having five feeders, and two having six feeders. Of the other eight burn-outs which did not shut down the sub-station, two were sub-stations having three feeders each, two having four feeders, two having five feeders, one having six feeders, and one having seven feeders.

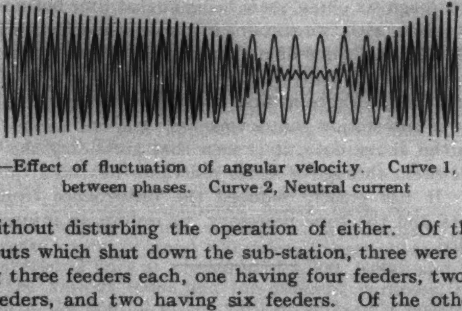

FIG. 3.—Effect of fluctuation of angular velocity. Curve 1, Potential between phases. Curve 2, Neutral current

Previously to the grounding of the neutral, the switches operated with explosive violence on the short circuiting of a cable, at times throwing oil and burning the contacts. Under present operating conditions, however, the switches always open very quietly, so quietly in most cases that it was necessary to install a tell-tale to indicate when there had been abnormal current through the neutral rheostats.

Before grounding the system, in all burn-outs the cable was so badly injured that it was impossible to make any bridge test, and it was necessary to open a great many manholes before locating the trouble. Of the sixteen burn-outs that have occurred since the grounding of the neutral, fourteen of them were in such condition that the fault could easily be located by the Murray loop method. In most of these cases but one leg was grounded. In the two cases where all three legs were grounded, making the bridge test impossible, the burn-out was the result of very severe mechanical injury. Locations of the fault are always made to within a duct length, even on the longest cables of more than 45,000 ft. The saving in time effected by this accurate predetermination of the trouble by the bridge method is an important factor in the time necessary to restore a sub-station to normal conditions of operation.

It is probable that something would be gained by increasing the resistance between the neutral and ground. When the scheme was first contemplated, it was planned to ground the neutral through six ohms, there being at that time but one power station. Now with two stations in parallel the effective grounding is through but three ohms, making the possible ground current twice that originally planned for. There is no doubt but that with the resistance as first decided upon there would have been fewer sub-station shutdowns.

From the above data, it is seen that grounding the neutral of this system through a series resistance has been quite successful. It has greatly reduced the disturbance from cable burn-outs and the time necessary to restore an injured cable to service.

DISCUSSION ON "THE GROUNDED NEUTRAL," AT NEW YORK, OCTOBER 11, 1907

Peter Junkersfeld: In November, 1900, the Commonwealth Electric Company of Chicago in one portion of its territory put into commercial service the first extensive system of four-wire, three-phase distribution at 4000–2300 volts. This 60-cycle system was soon installed in all the company's outlying and suburban territory, and has since grown to such an extent that the total length of three-phase or equivalent line of feeders to-day aggregates 525 miles, of which 55 miles is underground, the remainder overhead. The neutral of this 60-cycle system has always been connected solidly to ground.

In May, 1902, the Chicago Edison Company raised the voltage of its three-phase, 25-cycle transmission system from 4500 to 9000 volts, and put into service its first star-wound generator delivering 9000 volts directly to the bus-bars without step-up transformers. This system now aggregates 270 miles of three-conductor cable and is practically all underground, only nine miles being overhead. The neutral of this 25-cycle system has been connected to ground from the beginning. During the last year a part of this system has, however, been connected to ground through resistances. The remainder of the system during the last year and all of the system during the previous four years has been connected solidly to ground.

In June, 1907, the Chicago Edison Company put into commercial service its first 25-cycle underground line operating at 20,000 volts. The transformers were connected in delta at the receiving end and in star at the sending end. The neutral at the latter is connected solidly to ground.

The two companies mentioned above have recently been consolidated into the Commonwealth Edison Company, which thus operates a total of about 800 miles of three-phase overhead and underground lines at pressures of 4,000, 9,000, and 20,000 volts in the various zones and for different purposes, but on all of which the neutral either with or without a resistance is connected to ground. The experience in operating high-tension systems with the neutral grounded has, therefore, been considerable, and the engineering policy on this matter has been definite for several years. The experience, however, in grounding the neutral through a resistance is still somewhat limited. The various steps in this experience and development, and some of the reasons, with the conditions now existing, may be of interest in this discussion.

The 4,000—2,300-volt, four-wire, three-phase system of distribution in the outlying and suburban sections permits standard 2080 to 115–230-volt line transformers, thus giving a single-phase, three-wire lighting and small power service at 115–230 volts. It was felt that such a system of distribution would be unstable and would permit annoying and serious voltage fluctuations if the neutral of the primary system were not grounded. After considerable discussion the neutral was finally grounded, under the writer's direction, just before the first four-wire, three-phase circuit or feeder was put into service.

Among those who at that time (November, 1900) argued most strongly against the grounding of the neutral but who later, after making some experiments, became one of the most ardent advocates, was Mr. George N. Eastman, who, early in 1901, had occasion to make certain tests which led to a series of very careful investigations at a time when accurate information on this subject was very meagre. Some of the results of these investigations were presented by him in a paper before the Boston convention of the National Electric Light Association in May, 1904. These investigations, with the first few years of actual experience, practically fixed the engineering practice on this particular matter in the two Chicago central station companies, who have, since 1900, continued to develop their three-phase transmission systems with the neutral grounded.

We have no direct comparative experience with an ungrounded system under exactly similar conditions. The results from this grounded system have, however, been very satisfactory. There have been practically no underground cable burn-outs on this 60-cycle system, and comparatively little trouble on pot-heads or on the other overhead construction. The total number of transformer burn-outs from all causes, including lightning, overloading, and defects in the apparatus, during the last two years, has been about 1.4%, and 1.2% of the total number of line transformers in service. The percentage expressed in kilowatt capacity connected has thus far been even less. Similar, four-wire, three-phase systems with grounded neutral have during the last few years been installed in so many cities of the country that this practice has become quite well known. The grounding of the neutral on three-phase systems for general distribution has also become very common, at least in parts of Europe.

The 9,000-volt, 25-cycle transmission system in Chicago is used exclusively for transmission to sub-stations, not for general distribution. With the exception of a few induction motor driven exciters, all equipment consists of synchronous converters or synchronous motor-generators.

The present total continuous capacity of the two principal and two subsidiary generating stations is about 110,000 kw. The neutral of the 25-cycle, 9,000-volt system is, however, grounded directly only in the Harrison street and the Fisk street stations. The latter at present contains ten turbo-generator units, the first four of which were originally rated at 5,000 kw. and the last six at 9,000 kw. each, with the usual overload guarantee. The transmission lines from the two stations are operated normally as "radial" systems; that is, outgoing lines are independent of each other and are not tied together at the sub-station ends.

The neutral of this system was connected solidly to ground in May, 1902, when the first 9,000-volt generators were started at the Harrison street station. Since the Fisk street station was put in service, the transmission system has at times been operated all in multiple; at the other times, sectionalized. In the latter case each part or section of the system had a grounded neutral so as to avoid having two non-synchronous sections without a grounded neutral on each. At present, and during a large part of the last year, the entire 25-cycle system has been operated in two approximately equal sections, designated "System A" and "System B." Previously to this time the Fisk street station contained but four turbo-generator units, to which have since been added six units of a larger type with slightly different characteristics. Partly for this reason, and partly for the reason that with the rapidly increasing generating capacity it might be well to limit, in case of accidents, the possible flow of current to ground, there was installed a 0.5-ohm resistance between the neutral of each of the four new generators and ground. The four older generators are left with the neutral grounded solidly on each. Normally, the two sets of generators are operated on separate sections of the system, one of which was thus operated with, and the other without, a resistance in the neutral.

During the previous four years, or since May, 1902, the neutral had always been grounded solidly, and with satisfactory results. In case of a cable breakdown between conductors and ground, each cable was usually disconnected from the bus-bars by the overhead relays and oil-switch before the remaining two conductors became involved, thus permitting a quick and accurate location test by the Murray loop method. As the generating capacity of the system increased, and as it became necessary to have heavier overload and longer time-limit setting of relays on outgoing lines, the destructive effects of cable breakdowns have apparently been somewhat greater, although this may be due in part to the very heavy setting of relays. This indicated the desirability of limiting in some manner the current flow in case of accidents to decrease the destructive effects. It was also desirable to secure some comparative data on this matter of resistance or no resistance.

Four possibilities naturally presented themselves: 1, the design of generators with a lower short-circuit current; 2, grounding the neutral on only one of the groups of generators running in parallel, leaving the neutral open on the remainder so as to limit the flow of current to ground to the short-circuit current of the one generator; 3, the introduction of one large resistance between the neutral bus-bar from a group of generators and ground; 4, the introduction of a separate resistance between the neutral of each generator and ground. Partly for reasons previously stated, the latter method was adopted.

Both of the first two methods mean holding the neutral where it belongs, while both of the last two methods will cause displacement of the neutral with attendant rises in potential, as has been pointed out in Mr. Lincoln's paper.

In four cases of trouble, each affecting from 10 to 30% of the total service at the time, during the two years before the installation of resistances, and during the one year since, the effects might or might not have been modified if the neutral had been grounded with instead of without a resistance. In all the other cases of trouble during this period, and in most of the cases during the three years previously, the use of a resistance in the neutral would probably not have effected any improvement. In most instances the overload relays on feeder oil-switches were set at 100% overload for six seconds, although in some cases they were set at 100% for three seconds. The generator switches are all non-automatic and are opened only by the switchboard operator.

During the last five and one-half years, even after eliminating all cases of trouble which have no bearing on this subject of the grounded neutral, in addition to the four serious cases above mentioned, there have been quite a number of minor cases which have a strong bearing on the matter of the grounded neutral. Especially is this true of cable troubles which, during the last three years, have averaged only two cases per one hundred miles per year. This includes all troubles on 9,000-volt cables from known or unknown causes, except those due to external injury to the lead sheaths.

Notwithstanding these results, we have started some investigations with the oscillograph, and have also installed for purposes of observation some spark-gaps at different points on the system, all with special reference to securing more accurate information for guidance in the development of the 20,000-volt underground system into suburban districts. These investigations have not yet progressed sufficiently to afford much definite information. There are some indications that in the Fisk street station the spark gap when set for 100% above normal, discharges occasionally when the oil-switch on the distance sub-station end of the line is opened. This instantaneous rise of potential occurs even with the neutral grounded, and may be due to the stored energy of the line. We have thus far not been able to find rises of potential coincident with any other switching or other operation.

Our investigation and experience with one system for five years, and another system for seven years, leads us to believe, that between operating with the neutral grounded or not grounded, under our conditions the grounding of the neutral is the better policy. As to whether or not any additional benefits would be secured by grounding the neutral through a resistance, we feel that our experience is still too limited.

Philip Torchio: The papers presented by Mr. Rhodes and Mr. Clark give the experience of two moderately high voltage systems operated with grounded neutral. I shall contribute to their discussion the experience of the New York Edison Company's system which is also operated at moderately high voltage, but without grounded neutral. This comparison is not offered in a spirit of criticism of the admirable work described by Mr. Rhodes and Mr. Clark, but as an expression of opinion of those who have not yet found enough evidence of either the desirability or the necessity of grounding the neutral of 6600-volt, high-tension systems operated underground.

The Edison system operates at 6600 volts, three-phase, 25 cycles. The cables are mostly paper insulated, with $\frac{10}{32}$ in. insulation between conductors and $\frac{10}{32}$ in. between each conductor and ground. The feeders are operated on the radial system, not connected in multiple at the sub-stations. The system was started in 1898 with about three miles of high-tension cable, and grew steadily from year to year to the present system of about 200 miles. During the nine years' operation we have had 66 cable troubles of all kinds; of these, 32 developed during operation, and 34 were found either by the periodic insulation test or by inspection of the routes.

Table I gives a summary of all kinds of troubles divided into three classifications. In the first column are the operating troubles proper, cable troubles manifested during operation of the system; in the second column are cable troubles manifested when the cables were out of service, by periodic or special insulation test; the third column shows defective cable troubles found by visual inspection by the line inspectors. It must be noticed that the Edison Company's high-tension cables are distributed over all the city, where a lot of underground work has been done, causing a lot of interference and damage to the cable line. The table shows that there have been, in nine years, 32 operating cable troubles, 14 of which were due to mechanical injury. The majority of the troubles in the rest of the cases were in splices due to defective installation, etc.

If we eliminate the 14 troubles due to mechanical injury, and make allowance for the great amount of interference attendant to the subway conditions under which the New York Edison Company operates, we see that the number of troubles per mile of cable per year compares favorably with Mr. Rhodes' figures for the Interborough system. As to the extent of trouble caused by the cable burn-outs, in no case was the cable subway damage more than nominally.

We have been fortunate up to now in not having a severe blowing up of the subway cables, as mentioned by Mr. Rhodes. In one instance only the cable short-circuit was so severe as to overtax one of the old circuit-breakers—not of standard make—which caused a shutdown of the generating station. The short-circuit was caused by the driving of a pick into one high-tension

TABLE I

CLASSIFICATION OF ALL HIGH-TENSION CABLE FAULTS FOR THE PERIOD BETWEEN NOVEMBER 14, 1898, AND OCTOBER 8, 1907, INCLUSIVE

Manifested by opening of circuit-breakers during operation	Manifested by low insulation test	Reported by line inspectors
1. In splice	1. In splice	1. Injured in manhole by arc cable burn-out
2. Nail driven into cable (extraneous injury)	2. In splice	2. Nail into cable
3. In sharp bend in manhole	3. In splice	3. Damaged in manhole by alternating-current lighting cables burn-out
4. In damaged sleeve (extraneous injury, cause unknown)	4. In cable (steam exhaust)	4. In cable (extraneous injury)
5. In bend in small manhole	5. Moisture in old rubber splice	5. Damaged by outside parties doing subway work
6. Wet end of cable (extraneous injury due to water leak)	6. Moisture in old rubber splice	6. Damaged by outside parties doing subway work
7. In splice	7. Moisture in old rubber cable (extraneous injury)	7. Damaged by outside parties doing subway work
8. In bend (extraneous injury)	8. Nail driven into top conductor (extraneous injury)	8. Burn-out Fortieth street manhole, injury from adjacent cables
9. In bend—defective	9. In cable (steam leak)	9. Armor damaged by adjacent burning cables
10. In cable (possibly extraneous)	10. In splice (steam leak)	10. Armor damaged by adjacent alternating current burning cables
11. In splice	11. In defective splice	11. Armor damaged by adjacent burning cables
12. Drill forced through tile duct into cable (extraneous injury)	12. In cable (steam leak)	12. Armor damaged by adjacent burning cables
13. In splice (extraneous injury)	13. At splice end	13. In cable, damaged by adjacent burning cables
14. In splice (extraneous injury due to water leak)	14. At splice	14. Splice damaged by adjacent burning cables
15. In cable		15. Punctured splice probably due to surges
16. In splice		16. Damaged by outside parties doing subway work
17. In cable		17. Damaged by adjacent burning cables
18. In splice		18. Damaged by outside parties doing subway work
19. In cable (extraneous injury)		19. Damaged by outside parties doing subway work
20. Crowbar driven into cable (extraneous injury)		20. Damaged while doing excavation work
21. Puncture in straight section of cable (connected with station trouble)		

Manifested by opening of circuit-breakers during operation	Manifested by low insulation test	Reported by line inspectors
22. Ground detector acted in conjunction. Drill forced through tile duct into cable (extraneous injury)		
23. Ground detector acted in conjunction. Moisture in straight cable due to extraneous injury		
24. Ground detector acted in conjunction. Moisture in straight cable due to extraneous injury)		
25. Defective splice		
26. In easy bend in cable—connected with station trouble		
27. Defective splice		
28. Burns and mechanical injury to cable		
29. Damaged by adjacent burning low-tension cables		
30. Ground detector acted in conjunction. Defective cable in duct		
31. Defective splice connected with operating trouble		
32. Ground detector acted in conjunction. In straight cable—connected with station trouble		
14 Mechanical injury 8 At or in splice 4 In bends in manholes 6 In cables	5 Mechanical injury 9 At or in splice	19 Mechanical injury 1 At or in splice
32 Total	14 Total	20 Total

RECAPITULATION

38 Mechanical injuries
18 At or in splices
4 In bends
6 In cables

66 Grand total.

cable in proximity to the generating station. In other cases the relays and oil-switches cleared the short-circuited cable without affecting appreciably the bus-bar voltage.

Mainly on account of the large storage-batteries on the low-tension system, the effects of cable troubles have been considerably minimized. For the last three years all the cable troubles lowered the distributing voltage an average of 5% for 45% of the total system load with a total elapsed time of reduced pressure of 2.5 minutes. I omit other data corroborative of the general good results of the operation of this system and its freedom from violent disturbances due to cable burn-outs. Furthermore, in every instance when we had a burn-out or disturbance of any kind, we fully investigated all attendant circumstances and tried to figure out how the results might have been modified by having the neutral grounded. In no case of cable burn-outs did we find that the results might have been sensibly improved by the presence of the grounded neutral. On the other hand, station and sub-station troubles, which are usually minor but considerably more numerous than cable troubles, would in some cases have been made very serious by the presence of the grounded neutral. In the papers presented by Messrs. Rhodes and Clark no mention is made of these troubles inside the stations. But I think that they have an important bearing on the subject, and in most of the plants would weigh very heavily against the adoption of a grounded neutral without resistance, or with low resistance allowing ground currents considerably in excess of the condenser capacity current of the system.

Aside from these practical experiences, there is the theoretical side of the matter, which has been very ably treated by several prominent engineers in this country and abroad.* But unfortunately we know very little of the direct bearing of the theories applied to the operation of the underground systems now under consideration. And in this connection I want to make clear that none of the experiences with grounded neutral given here to-night claims that the grounded neutral. *per se*, will prevent violent surges on the system when under the provocation of a heavy two-wire short-circuit; that is, the grounded neutral has been made to assist in making the operation of certain mechanical relays and switches reasonably more positive than they would otherwise be. If for any reason a heavy two-wire short-circuit takes place, the presence of the grounded neutral is ineffective to change the results from those that would take place if the neutral were not grounded. Furthermore, by grounding the neutral without resistance, a dead short-circuit occurs on a cable every time the insulation resistance of the cable is reduced enough to let an appreciable amount of current pass to ground, while without a grounded neutral the operator might have time to disconnect the defective cable from the system before the ground had developed into a short-circuit. Now, the elapsed time between the beginning of the deterioration of the insulation around one conductor and its final dead grounding is usually very long. It may be several minutes, or hours, or days.

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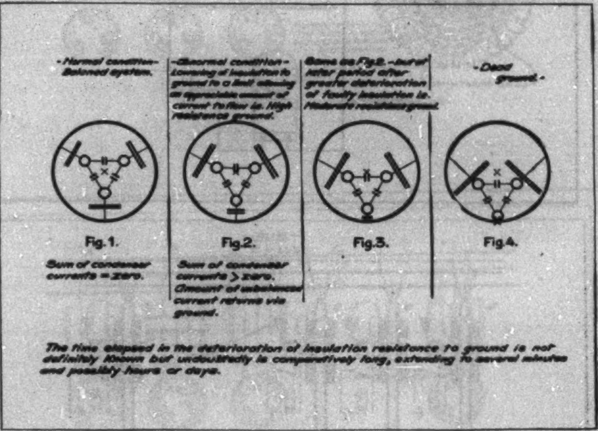
* Steinmetz, American Institute Electrical Engineers, 1901; Kennelly, Electrical World and Engineer, 1901; J. D. Nies, Electrical World and Engineer, 1902; Thomas, American Institute Electrical Engineers, 1902; G. N. Eastman, Western Electrician, 1903; G. H. Eastman, Electrical Congress, 1904; David, Societe Int. des Electriciens, 1904; Blondel, Societe Int. des Electriciens, 1905; Brylinski, Societe Int. des Electriciens, 1905; Steinmetz, American Institute Electrical Engineers, 1905; Thomas, American Institute Electrical Engineers, 1905; Patchell, Institution of Electrical Engineers, 1905–1906.

The speaker and Mr. T. W. Varley have taken advantage of this fact and have developed a device now being applied to the New York Edison system by which it is expected to obtain all the advantages of selecting and disconnecting the defective cable considerably before the condition of a dead ground is reached. The device can be operated on a system with or without grounded neutral. The device takes advantage of the unbalance of condenser capacity current on the cable system when the insulation of any conductor begins to deteriorate.

In Mr. Lincoln's paper there is shown very clearly the condition of an electrostatically balanced system, when there is no faulty insulation to ground; a similar diagram in Fig. 1, Plate 1, shows approximately the amount of capacity current between conductors, and the condenser current between each conductor and ground. The sum of these condenser currents under normal conditions is zero. If the insulation resistance to ground begins to get lower, and an appreciably small amount of current flows between one conductor and ground, there will be an electrostatic disturbance that will cause the different amounts of condenser current to vary proportionately to the discharge from the conductor to ground as shown in Fig. 2. It should be noted that the sum of the condenser currents is greater than zero, and the amount of unbalanced current would now have to find another path to the bus-bars, and that path is through earth.


-Normal condition-
Balanced system.
-Abnormal condition-
Lowering of insulation to ground to a limit allowing an appreciable amount of current to flow i.e. High resistance ground.
Same as Fig.2.-but at later period after greater deterioration of faulty insulation i.e. Moderate resistance ground.
-Dead ground.-
Fig.1.
Fig.2.
Fig.3.
Fig.4.
Sum of condenser currents = zero.
Sum of condenser currents > zero.
Amount of unbalanced current returns via ground.

The time elapsed in the deterioration of insulation resistance to ground is not definitely known but undoubtedly is comparatively long, extending to several minutes and possibly hours or days.

PLATE I

Fig. 3 shows the same condition as Fig. 2, but the resistance to ground is still lower, almost a short-circuit of conductor to ground. Fig. 4 shows the condition of a dead ground, as when all the capacity current of one conductor is discharged to ground.

Referring to Plate II, the device consists of a current transformer applied to the lead sheath of each feeder. The secondary of the transformer is connected by means of a condenser to a relay, which is intended to operate either the circuit-breaker or a signal similar to a telephone drop relay of standard make, as desired. This plate shows how the transformers are applied.

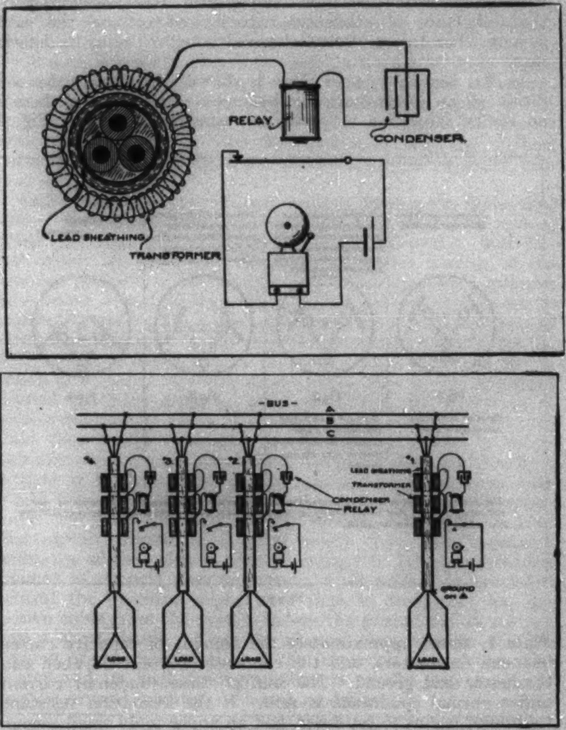
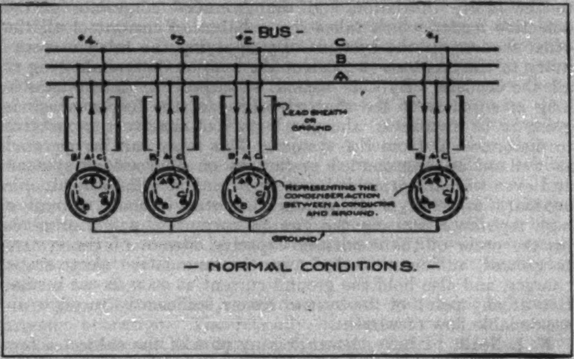

RELAY
CONDENSER
LEAD SHEATHING
TRANSFORMER
-BUS-
A
B
C
#4
#3
#2
#1
LEAD SHEATHING
TRANSFORMER
CONDENSER
RELAY
GROUND ON A
LOAD
LOAD
LOAD
LOAD

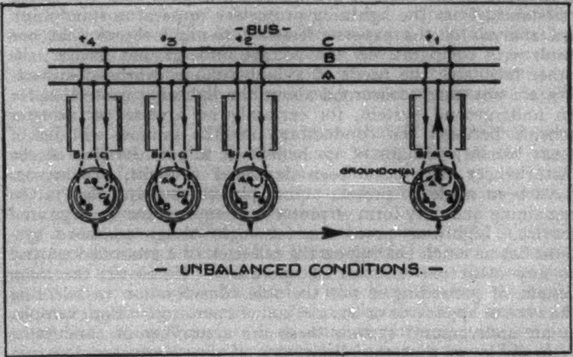
PLATE II

On each feeder we are putting on three of these transformers; they are about 6 in. long, and cover about 18 or 20 in. of the cable.

In Plate III are indicated a set of three-phase bus-bars and four high-tension feeders. The feeders can be extended to any number. The circles indicate diagrammatically the cable, and the segments of circles inside indicate the capacity current to ground of each conductor; and they are made equal, which indicates that the capacity currents in each cable are balanced and no current flows through the earth. The conditions of un-



- BUS -
#4
#3
#2
#1
C
B
A
LEAD SHEATH OR GROUND
B A C
REPRESENTING THE CONDENSER ACTION BETWEEN A CONDUCTOR AND GROUND.
GROUND
— NORMAL CONDITIONS. —



- BUS -
#4
#3
#2
#1
C
B
A
B A C
GROUND ON (A)
— UNBALANCED CONDITIONS. —

PLATE III

balanced capacity current as illustrated in Plate I, Figs. 2, 3, and 4 are covered by the arrangement of the devices shown in Plate III. When there is a dead ground, the condenser current of that wire disappears and the condenser current of the other two wires has grown to twice the size. The return for these unbalanced currents is shown by the arrows via earth to the faulty insulation and the grounded conductor of the defective feeder which takes the unbalanced current of all the other feeders on the system. By applying the relay in proximity to the bus-bars we detect the sum of the unbalancing of all the feeders By this means we expect to detect trouble long in advance of the short-circuiting of the feeder which is going to be in trouble, and give plenty of time to the operator to disconnect it from the system. This relay can be operated as well on an ungrounded system as on a grounded system· and even with the grounded system I think it will be a valuable auxiliary, especially if the grounded neutral is made through a high resistance limiting the ground current to a few amperes (in the order of the condenser capacity current of the system to ground) sufficient to discharge the cumulative electrostatic charges, and also hold the ground current as soon as the insulation at any point of the system lowers sufficiently to allow an appreciable flow of current.

N. J. Neall: I have chosen for my part of the subject a few comments on the effect of grounding the neutral with or without resistance, from the lightning protective apparatus standpoint. An analysis of the papers presented to-night shows that one deals with comparatively low-voltage underground service; the other intimates the needs of a high-voltage overhead system. We are not much concerned about the lightning protection for an underground system, for certainly no arrester or arrester scheme between the conductors and the ground will be of great benefit, perhaps of no benefit at all, in the line of the disturbances that have been described to-night. Endeavors have been made to protect across phases; perhaps that is the remaining and only form of protection required for underground service. Lightning protection for high-voltage overhead systems has as much bearing on the selection of a grounded neutral as any other one element of operation. Moreover, the mere benefit of grounding is not the sole consideration in selecting the type of apparatus or the method of operation. For example, in an underground system there are a number of conductors in multiple, so that the elimination of one conductor does not cut out the entire service.

The situation can be looked at from the standpoint of design or manufacture and also the standpoint of operation. Manufacturers I think, follow rather than lead in the adoption of high-voltage protective apparatus; so that as the contemplated voltages for commercial service get higher, it is very doubtful whether one can obtain arresters as quickly as one can get apparatus suitable for this service. Now, to ground the neutral would throw the arrester ratings into a group which has been already only partly developed. Moreover, the question of insulators for these high voltages is also an important element in the selection of the method of connection. Neither a grounded neutral nor an ungrounded neutral will save the puncturing of insulators by high-voltage strains induced by lightning. I do not refer to direct strokes, but to those concentrated charges that are known to exist on transmission lines and do not seem to be able to pass more than a few hundred feet at most from the point of application. It has been thought in times past that these charges jumped over the insulators, but it often happens that they cause punctures. Now, if a line be grounded, with resistance or without, and the charge just described takes place—discharging over the insulator—a short-circuit follows which might be of sufficient strength to shatter the insulator. If it be an ungrounded system, it might be merely a static discharge of the local condenser current, so to speak, which will not have heat enough and will be so attenuated that it will not cause anything further than a temporary disturbance of that particular part of the line.

A grounded neutral, moreover, does not help lightning-arrester operation. Theoretically, it throws more of a strain on the arrester at the time of operation than if the line were not grounded. The arrester, as Mr. Lincoln has said, can be insulated for a lower voltage and closer adjustment to the normal voltage of the line, but it is a grave question whether that is not offset by the fact that the arrester helps to form at the time it operates a partial short circuit on the system, provided the resistances do not give way under the strains, which is most doubtful.

Another element of line operation that is not helped very much by grounding is the telephone plant. One of the most serious conditions in long-distance transmission at the time of any disturbance is the interruption of telephone service within the transmission system itself.

If a resistance must be used—and there seems to be in certain cases good reason why this has been selected—it seems an easier matter to select a resistance suitable for low voltage than one suitable for high voltage. Those of us who have studied the resistance for lightning protective apparatus know that a resistance of small size, of small cost, of large current-carrying capacity, and current-choking capacity, is a very hard thing to get. The same problem in only a modified way exists in the high-tension system with the grounded neutral. I do not believe it is possible to predict any positive method of operation, but I should say, judging from the progress of the art, that if the apparatus can be made sufficiently insulated to be connected in delta, and lightning-arresters can be found that will operate nicely at that voltage, and proper provision is made for the sectionalizing of the line or cross-sectionalizing of the line if it happens to be a parallel circuit, that a minimum of interruption of service can be obtained. If in addition to this the progress of the art of lightning protection will indicate relief from a great deal of these induced disturbances that I have spoken of, and if the promise of electrolytic lightning-arresters can be fulfilled, a great deal that I have just said about lightning protection will be very happily modified.

John B. Taylor: The grounded nuetral with or without resistance must be regarded as a protective device, and for this reason the trend of discussion seems to be similar to discussions on lightning-arresters and choke-coils. Apparatus or devices which become operative only in emergency conditions cannot be subjected to tests that will absolutely determine their value for the emergency condition, hence the reported results of successful operation from plants where the neutral is grounded and also where it is not grounded.

Mr. Lincoln speaks of obtaining a neutral connection from "an auto-transformer connected to proper points of the delta." I have had occasion to make up stable artificial neutral points where no neutral is available on any of the apparatus, but my arrangements could not be described in his terms and I ask Mr. Lincoln to show us a diagram of the arrangement he has in mind.

In discussing the proper value of resistance in the neutral lead, Mr. Lincoln states that this resistance must be such as to pass sufficient current to trip the heaviest circuit-breaker. This requirement appears proper for feeder distribution systems which have already been referred to as "radial feeders," but these should be considered as a special rather than a general case. The general case where it will be found desirable to make use of resistance in the neutral, is a system mainly of underground cables, supplying a number of sub-stations, having two or more cables which are parallel on the sub-station bus-bars as well as on the main station bus-bars. A consideration of this interconnection of cables will readily show that the current flowing to ground at the cable fault will divide according to the resistance of the various branches, part flowing from the main station over the faulty cable which has to be cut out, the rest flowing by way of healthy cables, sub-station bus-bars, and faulty cable from the sub-station end. In general, then, the limited current must be at least twice that at which the circuit-breakers are set, and in addition to this there must be a liberal allowance for combined effects of conductor resistance, resistance at the fault itself, resistance of earth return, and drop in voltage at the generator. This requirement makes it difficult to make an entirely satisfactory application of the neutral resistance to systems that have heavy feeders and at the same time fluctuating load, so that only limited generator capacity may be at times in service, especially in the small hours of the night.

From the record of cable breaks, in Mr. Rhodes' paper, I have figured out the number of breaks per mile of cable per year. I think it a matter of interest that Mr. Junkersfeld's figures on cable breaks, on a 9000-volt system in Chicago, for 100 miles of cable per year, are very nearly the same. From Mr. Rhodes' figures the number of cases of burn-outs per mile of cable per year are slightly greater since the neutral was grounded. While the purpose of the ground in this plant is to secure selective operation of switches, yet I should look for a reduced number of burn-outs. With the resistance, grounds are more quickly removed, with consequent reduction in time of increased voltage strain on the whole system. Possibly the records do not cover a sufficiently long time to eliminate the element of chance; it is also possible that the increased number of faults since the resistance was installed are due to trouble in the joint, etc., incidental to the installation of a number of miles of new cable.

Mr. Clark's experience with neutral resistance is certainly interesting and I hope that he can give us some more data on the following points. What is the resistance of the plate ground? Why have they not availed themselves, in addition to the plate, of the extensive system of water pipes, etc., which is generally available in the neighborhood of any large generating plant? We have very little data on resistance of circuits with different earth terminals, and if Mr. Clark can advise how much the neutral resistance (given as 6.7 ohms) is increased by the earth resistance at the plate, we shall be indebted to him. I also hope that Mr. Clark will tell us the material of the neutral resistance, as cast-iron heated up to 1000° fahr. will practically double its resistance with corresponding reduction in current allowed to pass.

The assumption that the resistance will pass 1000 amperes, apparently makes no allowance for resistance in the rest of the circuit. Obviously, if conditions were such as to permit the flow of 400 amperes—and this is insufficient to trip the circuit-breakers—the neutral resistance could not be expected to accomplish much under these adjustments. I will ask Mr. Clark to tell us what the circuit-breakers are set at? and whether or not parallel feeders are interconnected at sub-station bus-bars?

I am also interested to know how Mr. Clark distinguishes alternating current shunted into telephone lines from alternating current with the same frequency induced in telephone lines. It is of course quite possible to have this current in telephone lines due either to fall of potential between two points in the earth, or due to induction, and I hope Mr. Clark will give a little more data on the local conditions showing that the alternating currents are due to conduction rather than induction.

Carl Schwartz: On account of the many variables connected with grounding the neutral of a three-phase generating and distribution system, a careful study of the individual conditions should govern a decision as to:

1 Whether the neutral should be grounded or not.
2 Whether directly or through resistance, and
3 If resistance be used, its amount and proper connection.

In the system referred to in the following discussion, the neutral is grounded through resistance, but partly owing to the fact that the system has been in operation for a comparatively short time, not very extensive experience has been gained. The only statement which perhaps can be made is that so far no trouble has occurred to reason against the arrangement adopted, nor have objectionable features appeared. There are two power stations, ultimately to contain six units of 5000 kilowatts, 11,000 volts, three-phase, 25 cycles each, and eight sub-stations, one power station with 20,000-kw. capacity, and three sub-stations in operation at the present time.

The neutral ground connections are arranged as follows:

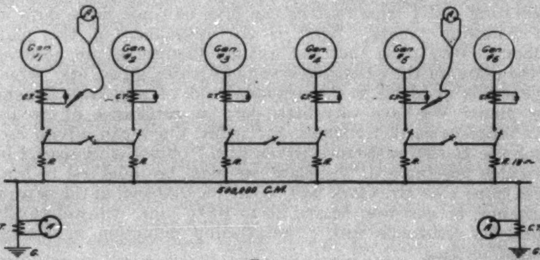


FIG. 1

Fig. 1. A bus-bar of ground potential, 500,000 cir. mils, grounded at both ends, runs through the station. To this are connected the neutrals of the individual machines through separate resistances. Disconnecting knife-switches between machines and resistances allow their separation as may be required.

The ground plates are of copper, about 20 square feet, and buried deep enough to be always under salt water. Current transformers are inserted in each neutral, and also in the ground connection. The secondary leads of the neutral current transformers are brought to the main operating switchboard and ammeters can be inserted in the circuits by means of plugs. For the neutral ground connections, however, the two ammeters are located on a record board in the office of the load dispatcher.

The former instruments are of little importance, while the latter indicate any ground or abnormal condition in the system and are used as "trouble indicators." The neutrals of two adjacent generators can be connected together by a tie-switch which is ordinarily kept open, and closed only in case one machine alone is running in a station, as one resistance alone would not allow sufficient current to flow to trip the feeder-switch relays.

The resistances are constructed of cast-iron grids, set in iron frames on porcelain insulators, and enclosed in fireproof brick compartments, with proper ventilation. The resistance of each of them is about 19 ohms, so that with a difference of potential between phases and ground of 6300 volts, about 330 amperes can flow through each resistance. From two to four resistances are to be used in parallel at one time.

There appear to be a few points in favor of the arrangement outlined, as follows:

1. It will be noted that two resistances, equal to about 38 ohms, are always in series between two machines, and experience confirms that practically no cross-current flows between the machines at the time of synchronizing or otherwise. A heavy, 75-cycle, cross-current flows if the neutrals are tied together directly, unless the field current can be adjusted to avoid this condition.

As Mr. Rhodes points out on the third page of his paper, these cross-currents may have a very serious effect on the operation of the station and interfere more or less with synchronizing of the machines. For instance, with a load of 1800 kilowatts on each of two generators, 90 and 160 amperes field current respectively, a cross-current of 130 amperes was observed. With 120 amperes field current on both machines, and 2100 and 600 kilowatts load, respectively, the cross-current was 65 amperes. In both cases the neutrals were tied together solid.

The difference in load in these particular instances was not very large, but the figures indicate the conditions to be expected with a greater difference or with improper field adjustment. This cross-current disappeared entirely with the resistance of 38 ohms inserted.

2. The main bus-bar has ground potential like all resistances and apparatus connected thereto and not in use. This would not always be the case were resistance inserted between the main bus-bar and ground.

3. The arrangement allows the testing of either ground connection; one of these can be opened any time for this purpose.

4. As not all the resistances are required for normal operation, the others serve as a reserve in case of a burn-out.

5. The amount of resistance to be inserted into the neutral ground connection can be sufficiently varied to suit different operating conditions, at the discretion of the operating superintendent.

C. W. Stone: With an ungrounded system a short-circuit is expected to open the feeder-switch. If the neutral of that system were grounded without a resistance, it would contribute to the chance of a short-circuit, because one phase to ground means an equivalent to a short-circuit and a consequent shock to the apparatus. It seems advisable, therefore, to put in a resistance to cut down the amount of current existing at this time, and for this reason I have always contended that the resistance should be inserted in the neutral.

In one of the papers it is stated that it seems inadvisable to put in a resistance for each unit, resulting in a variable resistance according to the number of units in service. This is true. But it seems to me that a larger current flowing through the circuit is not serious if there are more machines in circuit, and the relative effect on the system is no greater than if with the single resistance and only one machine.

Mr. Lincoln mentions the different points for grounding a system. I think it a bad plan to ground at more than one place. I know of one case where a lighting system was operated with the ground, not only in the main station, but in different sub-stations; and when a car started up in an outlying district the fluctuation in the lights was serious, due to the flow of direct current on this grounded connection, the neutral being a better ground return than the rails.

If the neutral be grounded on a high-tension system, and an automatic switch be used, three current-transformers will be necessary instead of two—and current-transformers are not the best things to use in a high-tension system.

Mr. Lincoln leaves wide latitude in the selection of the type of resistance. I think that care should be taken in selecting the type of resistance. I note in both of the other papers that iron grids have been used for the neutral resistance. I think this is objectionable, because there is no doubt but that there is a certain amount of reactance with the iron grid. Reactance in series with the condenser action of the cables is not good, as we all know. It therefore seems best to use some resistance with practically no reactance. In the case cited by Mr. Junkersfeld, they carefully avoided the iron grids and put in german-silver ribbon.

F. B. H. Paine: There are places where it is desirable to use a high resistance in the neutral in order to limit the current to a certain small amount, regardless of the amount of energy being sent out, or the number of generators in service. There is no difficulty in operating the main switch with this limited neutral current if a current transformer is placed in the neutral and connected through a relay to operate the main switch with the predetermined current in the neutral.

There is one case where it is desirable that the sub-station neutral at the end of the line be connected to ground through a resistance as well as that of the power station; that is, where this sub-station is connected to the source of power through fuses or other automatic apparatus which may open one leg of the circuit and leave the other legs connected, thus permitting the electromotive force of the unconnected wire to soar according to the static capacity of the line, transformer, connections etc. and resulting in injury to the sub-station transformer.

Chas. F. Scott: One point has received but little consideration, and that is the automatic circuit-opening devices. Relays and circuit-breakers have been mentioned, but their importance and their bearing upon the question now under discussion have not been fully brought out. One of the purposes of grounding the neutral is to facilitate the cutting out of a defective circuit. The presence of a permanent ground and the amount of resistance which may be inserted in it for limiting the current when one of the circuit wires becomes grounded are, therefore, very intimately related to the automatic opening devices. These devices are of various kinds. There must first of all be a discriminating, selective instrument which can recognize the conditions under which the circuit should be opened. Such an instrument may act upon overload or upon reverse current and it may incorporate certain time-elements. This device transmits its indication, usually through a relay, to the circuit-breaker. The circuit-breaker should be one which will act instantly and smoothly, cutting out the damaged circuit so quickly that the operation of the other circuits will not be appreciably affected. The action must be practically instantaneous in order to prevent a drop in potential on the system in general, which would affect the running of synchronous apparatus. The opening devices must, therefore, provide for action not only in case of a ground on one wire but also when there is a short-circuit between two of the wires. The whole matter of automatic circuit-opening devices is, therefore, very intimately connected with the grounding of the neutral. This indicates some of the various ramifications of the general problem of grounding the neutral in an operating system.

The discussion this evening confirms an opinion that I expressed some time ago with regard to experience with grounded neutrals. I said that so far as I had been able to determine, the managers of those plants which operate without a ground abhor grounds of all kinds and would not think of purposely grounding any point on the system. On the other hand, others who have operated with a grounded neutral place great reliance for safety and reliability upon the fact that the neutral is grounded, and would not think of operating in any other way.

Paul M. Lincoln: Answering Mr. Taylor's question as to the method of obtaining a neutral in the delta connected system, there is no particular difficulty about this matter. In the absence of a blackboard, if Mr. Taylor will imagine an equilateral triangle as a three-phase system, a conductor at each corner, then the neutral of that system will be at the centre of that triangle. Now, draw a line through the centre and let it intersect the side where it will, and call that line which you have drawn through the centre an auto-transformer, with a number of turns proportional to the length between the centre and the points where it intersects the side, that will be the proper connection for an auto-transformer to obtain a neutral. For instance, if one end of the auto-transformer be connected to the middle of one side of an equilateral triangle, and the other end to the opposite corner, so to speak, then the neutral will occur at a tap in the auto-transformer winding such that there is one turn in the section between the tap and the middle of our equilateral triangle to two on the opposite side.

Another point which Mr. Taylor mentioned is that in cases of multiple-connected feeders, a short-circuit occurring at a point near the farther end of these feeders, the ground currents will divide nearly equally between them.

The point is well taken, but is not at variance with the statement in my paper that, " the resistance must be small enough to permit sufficient current to flow to trip the heaviest circuit-breaker on the system ".

Mr. Stone has raised the question as to relative advantages of a resistance in the neutral of each generator as against one resistance for all. So far as the action upon the windings of the generator is concerned, the former is the logical method of operating, because the resistance in neutral of each generator will limit the current which can flow through that particular generator to the point that the resistance is adjusted for. However, that is not the only point to take into consideration when fixing the neutral resistance. Of more importance than the destructive effects on the windings is the damage which will occur at the point of breakdown. Where the current is large, the damage at the point of breakdown is bound to be large, and I believe that limiting the damage at the point of breakdown is one of the great functions of resistance in the grounded neutral. Limitation of damage at the point of breakdown requires a fixed resistance rather than a resistance dependent on the number of generators in circuit.

George I. Rhodes: The object of the neutral resistance is to minimize the effect of a ground and still remove the damaged feeder. With a single rheostat, the possible disturbance to the generating system will be a maximum with one machine running, and a minimum with all generators on the line. With a separate rheostat for each generator, the relative disturbance will be the same at all loads. In either case, the effect will be the same with a single machine on the line, hence a constant resistance will give the better results when more than one generator is running.

In an underground system such as that of the Interborough Rapid Transit Company, a ground on a cable is invariably followed by a short-circuit when the neutral is insulated. I do not see any way in which grounding the neutral can increase the number of short-circuits. In most of our burn-outs since grounding the neutral, the switches have opened very easily without evidence of heavy currents.

The inductance of cast-iron grids is very small. Our 6-ohm rheostat has a reactance of about 0.3 ohms at 25 cycles. In view of the large inductance of the generators and transformers on the system, this small increase can have very little influence on resonance effects.

Chas. P. Steinmetz: In the early days of designing high-potential long-distance transmissions, engineers were very careful thoroughly to insulate every part of the system from ground. In later years grounding the neutral was tried, and the results were so satisfactory that the practice found extended acceptance and many engineers since that time have recommended grounding the three-phase neutral. While I do not believe in promiscuous grounding, I recognize that in many cases a great advantage results from grounding the neutral of a three-phase system. It seems to me that the conditions in this respect are about as follows:

1. *The neutral of the three-phase system should not be grounded where grounding is not necessary.* Grounding the neutral introduces the liability of a number of troubles and disadvantages, for any ground on a conductor of a system with the neutral grounded is a short-circuit, and shuts down the system or a part of the system. Theoretically it is true that with one conductor grounded and cut off by some automatic device the three-phase system can be operated with two lines and the grounded neutral as the third. This is called the "inverted three-phase system". But this practice is not always feasible or safe; and just in those cases where grounding is especially desirable to maintain the electrostatic balance of the system, this inverted three-phase system, which is electrostatically unbalanced, would very likely be inoperative—it might lead to high-frequency oscillations and other serious disturbances.

There is an essential difference in this respect between Western long-distance transmission lines and Eastern underground cable systems. Many things that are feasible and safe on a long-distance transmission line would prove disastrous in an underground cable circuit. Where the resistance of the circuit is large, so large that the effect of the resistance is comparable with that of the capacity, as is usually the case in a long-distance transmission line, it frequently is feasible to operate safely with an unbalanced electrostatic condition. It is also feasible to dead ground the neutral, the currents being limited, and oscillations, high-frequency disturbances are damped by the dead resistance. In an underground cable system the problem of keeping down the temperature of the cable, with its poor heat-radiating capacity, limits the resistance of the cable to such values that the resistance effect is practically negligible compared with the capacity effect. In such a case, the damping effect of the circuit resistance is small, the volume of current passing over an oscillating arc is large and correspondingly dangerous, and frequently the operation of the system when electrostatically unbalanced is not feasible, or at least unsafe. The experience with such low-resistance cable systems is then quite different from that with high-resistance long-distance transmission lines.

Another difficulty liable to result from grounding the neutral is ground currents, which may reach serious values, flowing over the neutral, especially where several neutrals are grounded, the current flowing between generator neutral and generator neutral, or between transformer neutral and transformer neutral; or, which is usually the most vicious case, between generator neutral and transformer neutral, in the latter case overheating the transformer by excess current even at no load.

Another trouble is that grounding the neutral superimposes upon the pressure difference between ground and line an additional electromotive force, usually of treble frequency, generated in the generators or the transformers. This changes the wave shape of the potential difference between the ground and line, produces a sharp peak, and raises the potential difference of the conductors against the ground by sometimes as much as 40 per cent. and more beyond their normal values. These higher frequency voltages may lead to serious surges or high-voltage oscillations, due to the building up of the voltage by the capacity of the circuit between line and ground being in series with the inductance of transformers or generators in the circuit of these treble-frequency electromotive forces.

Furthermore, telephone disturbances are liable to result from grounding the neutral, electrodynamic induction due to the currents flowing over the ground, or electrostatic induction due to this treble-frequency electromotive force appearing between line and ground. I have known a number of instances where the ground had to be taken off the generator neutral because of telephone interference.

2. *The neutral should be grounded if the system cannot be operated safely when electrostatically unbalanced.* The three-phase system with grounded neutral is electrostatically balanced; that is, all three conductors have equal potential differences against ground. The three-phase system without grounded neutral, in normal condition of operation, is also electrostatically balanced, and the three conductors have equal potential differences against the ground, and the electrostatic relations are the same as in the grounded system. If, however, a ground appears on one of the phases in the ungrounded system, then electrostatic unbalancing occurs and the other two line conductors rise to full potential difference against ground. In this case the grounded system shuts down.

There are two kinds of electrostatic unbalancing by grounding one conductor: first, by a continuous ground or dead ground; secondly, by an intermittent or oscillatory ground, as an arcing ground or spark discharge. The electrostatic unbalancing due to the continuous or permanent ground on one phase leads to a higher potential difference between the other two phases and the ground. This may be serious in a system of very high potential, as 100,000 volts. As a rule it would not be serious, but should be well within the margin of insulation safety of an ordinary medium or high-voltage system. The effect of this unbalancing is that lightning-arresters discharge when set close to the normal voltage, so as to afford efficient protection, because during ground they are receiving 73 per cent. more voltage, the full delta voltage instead of the Y voltage. In an ungrounded system, then, the precaution must be taken to arrange a number of additional spark-gaps so that they are automatically thrown into the lightning-arrester circuit, to raise the discharge voltage up to the voltage which in this case exists between line and ground. This can easily be taken care of automatically, as by a fuse shunting these auxiliary spark-gaps, the fuse opening when at the higher voltage the arrester begins to discharge continuously.

There is also to be considered the electrostatic induction from the unbalanced high-potential circuit to lower potential circuits, related to them by step-up or step-down transformers, which may give very serious potential differences; for instance, between the low-potential generator circuit and ground, thus leading to a breakdown in the generator system, or in a primary distribution system, at 2200 volts, fed by the high-potential line. Protective devices are therefore required on these low-potential systems; but aside from this the continuous ground seems to be of minor importance, different from the intermittent or oscillatory ground. The latter leads to serious high-potential, high-frequency disturbances, which may cause rapid destruction. I believe that these are the main causes of the breakdowns in ungrounded underground cable systems where the operation has not been quite successful. Here again is seen the great difference between the high-resistance, long-distance transmission line in which the oscillating discharge over an arcing ground is of very limited volume, due to the high resistance of the line, and the condition in an underground cable system of negligible resistance, where the volume of this high-frequency oscillation is such as to lead to rapid destruction.

In an overhead line this oscillation may finally lead to a permanent ground, while in a cable system it would lead to a short-circuit between the phases. Those arguments against using isolated systems, because such an oscillating arc would lead to a short-circuit between phases, apply only to the underground cable system and not to the overhead line. Where, therefore, such an oscillating ground leads to dangerous results in a high-potential system, it is advisable to ground the neutral.

3. *Wherever it is not necessary to have more than one ground*

on the system, it is desirable to ground the neutral at one place only. Several grounds are necessary where the circuit extends over so long a distance that the inductance between the ends of the circuit is too large for the ground on one end to safeguard the electrostatic balance against a high-frequency disturbance at the other end of the circuit. In this case both ends of the transmission line must be grounded. Otherwise multiple grounding is undesirable, since it introduces the danger of currents passing over the ground through the neutral, thus leading to electrodynamic induction, as on telephone circuits, to overloading and heating of apparatus by ground currents, and other troubles. Since no apparatus is in circuit at all times, with one ground only some method of switching the ground, or the use of a grounding bus-bar, is necessary to insure one ground being on the system. If it is desired to use the ground as an emergency return circuit, naturally grounds on both ends of the lines are needed, but I do not believe this practice is to be recommended, except for very low power in rather less important lines.

4. *Whenever it is not safe to ground without resistance, resistance should be used in the ground circuit.* Grounding without resistance becomes unsafe in a system of large power, for there would be a severe shock on a system with a grounded neutral if one phase grounds, resulting in a short-circuit. Furthermore, there is the possibility of an electromotive force of treble frequency appearing between the ground and the line, which with a dead-grounded neutral is liable to give rise to serious surges in the system between lines and ground, which are overcome by a resistance in the ground circuit. Therefore, to guard against surges between lines and ground, resistance is desirable in the ground circuit; occasionally it is absolutely necessary. In this case a single resistance is sufficient to dampen and so make harmless an oscillation between lines and ground.

To limit the cross-currents between the grounds of different generators, or generators and transformers, a number of resistances are necessary, one in each generator or transformer neutral. The resistance should be as high as possible so as to produce but little disturbance or shock on the system, and rapidly to damp any oscillation that may arise from a grounded neutral. The resistance should be low enough to act as a ground; that is, to insure a flow of current large enough to open the heaviest circuit-breaker, and thus cut off the damaged part of the system.

Obviously, the resistance should be non-inductive and should be permanent; that is, should withstand excessive overloads, because the current which flows over the resistance in normal operation is insignificant compared with the current which flows in the case of an emergency as a ground on one line. I believe this fairly excludes the use of wire-wound resistances as liable to be inductive, and it also excludes the use of such mixtures of clay and graphite as have been mentioned, which are very inconstant in their resistance when exposed to high temperatures and excessive overloads. The requirements, however, seem to point especially to that class of resistances which decrease in resistance with increase of current, the pyro-electrolytes, because such materials would permit the use of a rather high resistance between ground and neutral, thus passing very little current at normal operation; while in case of a short-circuit by a ground on one line, they rise in temperature and decrease in resistance rapidly and then pass a current amply large to open the circuit-breaker and cut out the disabled feeder. That would also give the advantage of introducing a time-limit into the operation of the resistance.

5. I desire to draw attention to a general principle based on human nature, though it has some exceptions. Where the trend of the times is very strong in one direction; for instance, in favor of using induction motors instead of synchronous motors, or vice versa, or grounded neutrals instead of ungrounded neutrals; wherever a case occurs in which it is doubtful whether one should do one thing or the other, it is usually safe to decide against the favored practice, for the reason that no one can remain entirely unbiased in his judgment if the general trend of sentiment is in a certain direction. Where one therefore thinks the advantages about equal, in most cases he unintentionally favors that side which is the fad of the time, and the impartisan argument therefore would be more in favor of the other side.

Frank G. Baum (by letter): The advantages of the grounded star connection over delta for high-voltage transmission (from 60,000 upwards) are as follows:

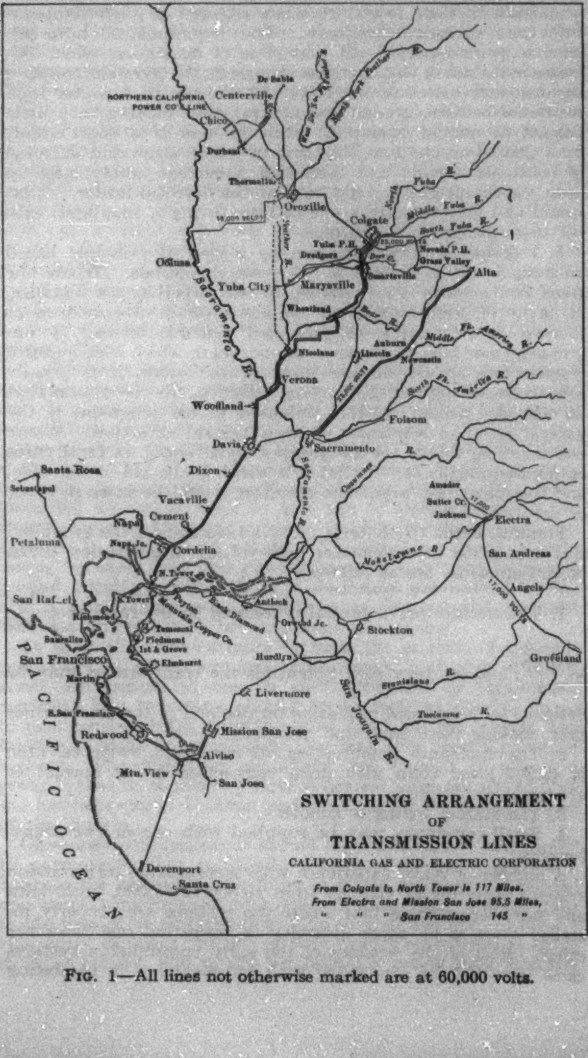
1. The transformer potential is reduced in the ratio of $\frac{1}{1.732}$ $= \frac{0.58}{1}$, and for very high potentials the transformers may be designed for reinforced insulation on one end of the transformer only, making them safer and cheaper.

2. The maximum potential on all insulators, switches, etc., is 42.2% lower than with delta connection under normal or abnormal conditions.

3. The station wiring is simpler.

4. Small consumers may be supplied with one or two transformers.

A number of years' experience with several large transmission systems operating at voltages from 10,000 to 75,000, both delta and star, demonstrate that where the systems are properly installed there is no more difficulty in operating one than the other. Most of the troubles of the early transmission systems came from lack of insulation; with improvement in insulation


De Sabla
NORTHERN CALIFORNIA POWER CO'S LINE
Centerville
Chico
Durham
Thermalito
Oroville
15,000 VOLTS
West Br. No. Fk. Feather R.
North Fork Feather R.
North Yuba R.
Middle Yuba R.
South Yuba R.
Colgate
Yuba P.H.
Dredgers
23,000 VOLTS
Nevada P.H.
Deer Cr.
Grass Valley
Smartsville
Alta
Oduna
Feather R.
Yuba City
Maryaville
Wheatland
Bear R.
Sacramento R.
Nicolaus
Auburn
Lincoln
Newcastle
Middle Fk. American R.
South Fk. American R.
Verona
Woodland
Folsom
Davis
Sacramento
Dixon
Cosumnes R.
Santa Rosa
Sebastapol
Vacaville
Cement
Napa
Amador
Sutter Cr.
17,000
Jackson
Electra
Petaluma
Napa Jc.
Cordelia
Mokelumne R.
San Andreas
N. Tower
S. Tower
Peyton
Black Diamond
Antioch
Mountain Copper Co.
San Rafael
Richmond
Temescal
Piedmont
1st & Grove
Elmhurst
Sausalito
Oxwood Jc.
Stockton
Angels
17,000 VOLTS
San Francisco
Hurdlys
Groveland
PACIFIC OCEAN
Martin
Livermore
Stanislaus R.
San Joaquin R.
S. San Francisco
Tuolumne R.
Redwood
Mission San Jose
Alviso
Mtn. View
San Jose
Davenport
Santa Cruz

SWITCHING ARRANGEMENT
OF
TRANSMISSION LINES
CALIFORNIA GAS AND ELECTRIC CORPORATION

From Colgate to North Tower is 117 Miles.
From Electra and Mission San Jose 95.5 Miles,
" " " San Francisco 145 "

FIG. 1—All lines not otherwise marked are at 60,000 volts.

there disappeared nearly all the troubles variously ascribed to "static charges", "lightning", "ground currents", "telephone and telegraphic interference", etc.

Fig. 1 indicates the area covered by the California Gas & Electric Corporation. On this system there are now operating about 75,000 kilowatts in water-power units, and about 30,000 kilowatts in engine units. The generators are star and delta connected, about equally divided. The star-connected generators are not grounded.

Most of the lines are star-connected for 60,000 volts, but other lines are operated delta-connected from the same generators. There are about 1000 miles of circuit at 60,000 volts; 250 miles at 10,000 to 40,000, and 125 miles from 4000 to 10,000 volts. The distributing lines are star or delta, as desired. There are over 100 sub-stations connected to the lines, a great many of them without operators.

The entire system is operated in parallel as a unit, and all the 60,000-volt lines are in parallel. The lines, transformers, etc., are switched in and out of service under any condition of load or short-circuit, and are handled in every respect in switching as though they were 2300-volt lines.

For very high voltage systems I see no reason for adopting anything but a star connection.

O. S. Lyford, Jr. (by letter): This is a subject which has as many sides as there are people interested in it. The grounded neutral is a sort of antitoxin administered, not to prevent initial distemper, but to keep it from spreading. The danger is that the remedy may prove more serious than the disease, or that the handicap to the general elasticity of the system may be greater than the immunity obtained.

When the neutral ground is adopted, its group of evils is accepted as the lesser of two. There is greater flexibility and greater convenience in the use of apparatus if the system is ungrounded. I refer particularly to the use of transformers in delta and the ability to operate with only two of the three. This advantage has led to the use of delta-connected transformers in the great majority of transmission systems, and this grouping of transformers prohibits the use of a neutral ground except by adding more transformers from which a neutral connection may be brought out.

As has been stated, the grounding of the neutral does not decrease the normal working strains or reduce the number of initial disturbances; furthermore, it does not prevent the first surges which may follow an insulation failure. When used, it is generally in the hope that it will minimize the abnormal voltage between line and ground and insure prompt action of the automatic circuit-breakers which will cut off the defective circuit before the damage is extended or the system as a whole shut down.

There are many cases where even the subsequent troubles, may not be prevented by a grounded neutral. Last year a case in point was reported which affords an illustration with a ludicrous side. A high-voltage line in Montana, having a pole spacing of 200 feet, lost a pole. As a result the wire crossing a cattle ranch hung about four feet from the ground. A steer came along to investigate, put his head over the wire and "got it in the neck" literally. Steer No. 2 came along, took a smell of No. 1 and fell dead. Steer No. 3 smelled of No. 2 with corresponding effect. Nos. 4, 5, etc., did likewise until there were half a dozen or more lying dead in a row.

A grounded neutral would not have reduced the amount of fresh beef materially, for even if the circuit-breakers had opened after each smell the operator would have had no alternative but to close the breaker again, making everything ready for the next. With a long line extending across the country the principal problem is not how quickly can one cut off a defective line, but how quickly can the defect be removed and to what extent can one operate until the defect is removed.

We had one case where one wire of a 15,000-volt three-phase transmission line operating a number of converter sub-stations broke and one end laid on the ground all day without causing any interruption of the service until the next morning when attempt was made to start up the system and it was discovered that only one phase was operative. This would not have been possible with a grounded neutral. We had another case, on the system to which Mr. Clark refers in his paper, where the object of the grounded neutral was defeated in a very fortunate way. The poles of the 11,000-volt trunk line of this system are of steel and are carefully grounded. The cross-arms, however, are of wood. In this case lightning struck the line, shattered some of the insulators and at least one of the wires was left lying on the cross-arm. The current was put back on this circuit and operation continued for some hours until repairs could be made conveniently.

All of this does not prove that the grounded neutral should not be used, but that it is by no means a cure-all; many times it is a positive detriment.

Referring to Mr. Lincoln's list of advantages and disadvantages, there is not much weight to advantages *a*, *b*, and *c*. Although a slight reduction in first cost of equipment may be effected by using weaker insulation, this insulation must be sufficient to resist lightning strains which are greater than any due to a ground on one leg. Static induction in neighboring circuits is seldom a serious matter and can usually be taken care of in some other way. The regular use of the ground as a conductor is a practice that can be adopted in only a certain few instances.

Advantage *d* is the main one, and on the other hand the principal disadvantage, although referred to later in Mr. Lincoln's paper, is not mentioned in the list; namely, the increased damage which may result to the generating apparatus and in some instances to the transmission system

Referring now to the use of a resistance in the ground connection of the system; this is really a compromise. With a neutral dead-grounded, any insulation failure in or near the power house means a practically dead short-circuit on the generators. Such a shock to the system is a serious matter which must be avoided as far as possible. It is inevitable with a short-circuit between phases, but there are few such short-circuits compared with the number of grounds, and one hesitates to adopt a measure which makes these grounds equivalent to short-circuits. The seriousness of these shocks develops, even if the short-circuit is of very short duration. Even fuse-testing in the immediate vicinity of the power station has caused displacement of the generator armature coils. Turbo-generators of high potential are peculiarly vulnerable in this particular.

In the case referred to by Mr. Clark, the neutral ground was adopted principally because of the unusual arrangement of overhead and underground circuits with many possible combinations which may tend to resonance. The object desired was to cut off a defective circuit before such a result should follow. The resistance was placed in the neutral circuit to minimize the shock to the system. This system is laid out with the expectation that there will eventually be 38,000 kw. of generating capacity in the present station, (or possibly double this amount), another power station operating in parallel with this, and a greatly extended underground and overhead transmission system.

As the ultimate conditions are approached, the advantage of limiting the current in the neutral circuit will increase. As matters now stand, the combination of equipment is such that we might expect very satisfactory results with either an ungrounded system, a dead-grounded neutral or a neutral grounded through resistance. There would undoubtedly have been fewer short-circuits, if there had been no neutral ground; on the other hand the character of the protective devices as a whole is such that very few of the interruptions have materially affected the service. As Mr. Clark points out, out of the 70-odd disturbances two would have been handled better with a dead grounded neutral. Neither of these two were very serious, however, and they do not in themselves prove that a change to one of the other combinations is preferable. Damage to the power station equipment by the surges which might occur without a neutral ground or by the shocks which might occur with a dead grounded neutral would result much more seriously.

It is an interesting fact that three of the most important systems, one of which was started without a neutral ground, and two of which were started with neutral dead-grounded, have for different reasons subsequently adopted a neutral ground through a resistance or resistances.

For the general case, it may be said that the ungrounded system is preferable, the exception being where there are special conditions which make an interruption of service on a particular circuit of less importance than the consequences if the defective circuit is not immediately cut off. If the system is a large one and conditions necessitate a neutral ground, present experience indicates that there should be a resistance in the neutral circuit.

George I. Rhodes (by letter): There were one or two questions asked during the discussion which I did not care to answer without looking further into the facts.

Mr. Torchio remarked that no mention whatever was made of troubles inside the power and sub-stations which were increased by, or the result of, the grounded neutral. The reason for the apparent omission is that there have been absolutely no station troubles which would not have occurred with equally bad results had the neutral of the system been insulated.

The only possible station troubles that can be increased or affected in any way by the presence of the grounded neutral are grounds on the station bus-bars, wiring, or transformers. Let us consider the effect of a ground on the power station bus-bar under the conditions of operation described in the writer's paper. If but a single generator is in operation, the station will be shut down. If more than one is on the line, that machine whose neutral is grounded will be removed from service, the remaining generators carrying the load. Even with but two generators in operation the remaining machine can easily carry the 100% overload for the short time necessary to get another machine into service. After changing over to the auxiliary bus-bar, the neutral of one machine can again be grounded and condition of normal operation resumed without interruption of service.

With a ground on the sub-station bus-bar, the sub-station will be shut down if the total current required to operate the relays is less than the maximum possible current to ground. If the relays require more current than this, the sub-station will continue in operation, but the generator whose neutral is grounded may be shut down. If a ground occurs on the sub-station bus-bar when the neutral is insulated, it will be impossible to remove this ground without first shutting down the sub-station on account of the large current flowing to ground (about 160 amperes).

It is to be seen, then, that with the neutral grounded, grounds in the power and sub-stations may seriously affect the continuity of service only when a single generator is running.

Mr. Taylor called attention to the fact that since the neutral of the system has been grounded, the burn-outs per year per mile of cable have been more frequent than before. He suggested that perhaps this was due to the large amount of new cable installed. This is undoubtedly true to a certain extent, but it must be remembered that the amount of new cable in the original installation was almost as great. He also suggested that the time was so short that the element of chance was not removed. I fully agree with this.

However, I have made a further study of the burn-outs occurring before and after the grounding of the neutral. In the original paper the writer gave a number of distinct operating burn-outs—12 before grounding and 16 after. Of these, there are known to be due directly to severe external mechanical injury, one before grounding, and seven since. Eliminating the latter, there are left 11 burn-outs before the grounding, and 9 after, which were due to internal causes. The writer believes that these burn-outs alone should be used in determining whether or not grounding the neutral has increased the number. Previous to grounding there were operated approximately 620 year-miles of cable, and since then there have been 660 year-miles. This gives the burn-outs per year per mile of cable due to internal causes 0.018 before, and 0.014 since the grounding. It thus appears that the grounded neutral has actually reduced the number of burn-outs that are not traceable directly to mechanical injury.

A paper presented at the 222d Meeting of the American Institute of Electrical Engineers, New York, November 8, 1907.

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COMPARATIVE PERFORMANCE OF STEAM AND ELECTRIC LOCOMOTIVES

BY ALBERT H. ARMSTRONG

So many excellent papers bearing upon the subject of steam road electrification have recently been presented to the engineering public that the writer hesitates to add to their number. In the hope, however, of offering a somewhat clearer insight into the fundamental reasons underlying the electrification movement, this paper is written from the standpoint of a technical comparison of the performance of steam and electric locomotives.

Among the many electrification projects now in course of construction, nearly all were inspired by such motives as cleanliness, smokelessness, convenience, etc., but few indeed have been considered strictly from the standpoint of direct financial benefits to be obtained. The improvements in and around New York City terminals, the various tunnel projects such as the early Baltimore and Ohio installation, and later the Sarnia, Detroit River, and Cascade Tunnel projects—all are examples of steam road electrification in which there were distinct reasons for displacing steam as a motive power, but there are other sections of our steam lines where these same reasons do not apply with equal force, and benefits of a more far-reaching nature must be made evident before such electrifications can be considered as necessary or desirable. It is concerning these other sections of steam lines demanding other reasons for electrification that this paper is written, and the best means to be employed in getting a thorough grasp on the subject seems to lie in an investigation into the comparative inherent qualities of steam and electric locomotives.

Before considering the electric locomotive, much the simpler of the two, it is advisable to determine the general characteristics and limitations of the steam locomotive viewed from the standpoint of the electrical engineer, in order that the scope of the problem may be thoroughly understood and the lines of contrast be sharply drawn

This preliminary study of the steam locomotive is made necessary by the fact that railroad practice to-day is essentially *steam* railroad practice and is hedged about by practices and methods of operation demanded by the use of the steam locomotive as a type of motive power. Viewed in the light of greatest benefits to be secured, the coming of the electric locomotive is not due to petty economies affected in coal consumption and cost of locomotive repairs; indeed, with coal as a common source of power, little gain in efficiency is secured through burning the same grade of fuel under stationary boilers over the excellent results obtained with the highly perfected modern compound locomotive. As will be discussed later, there exist certain fundamental relations between the cost of producing a horse power at the drivers of a steam locomotive burning its fuel on the structure, and a horse power at the drivers of an electric locomotive deriving its energy from a distant stationary power house via a distribution system. The use of water power, or of a cheaper grade of fuel than can be burned on a steam locomotive, will in many cases afford a means of reducing the fuel cost well below the present cost of high-grade coal required for successful locomotive operation; but in general the fuel item reduction does not in itself offer a sufficient saving to pay an adequate return on the large investment required for electrification.

It is necessary, therefore, to look for more far-reaching benefits, and, not considering the reasons governing the introduction of the electric locomotives at terminals and in tunnels, we find in a comparison of the characteristics of the steam and electric locomotives a contrast so marked that it shows not only the superiority of the electric locomotive for general railway conditions but it also suggests changes of a fundamental nature in present methods of operation now necessary with steam locomotives. And these benefits to be secured occur not only in the operation of passenger trains, but are felt to an even greater degree in the haulage of the heaviest freight trains, a field supposedly the exclusive domain of the steam locomotive.

The steam locomotive has two component parts, the boiler and the engine, both of which have their own individual characteristics; and the relation between the two is generally determined by the character of the service for which the locomotive is desired.

The steam locomotive boiler is universally of the fire-tube type, though experiments with water-tube boilers point to certain possibilities in this direction. Owing to the restrictions of width and length available, the locomotive boiler must of necessity be worked to its limits in order to generate the greatest amount of steam possible. It is not the purpose of this paper, nor is it necessary, to go into a detailed discussion of the proper relation between grate area and heating surface, fire-box construction, length of tubes, diameter, etc., all constituting improvements in locomotive design directed to the better evaporation of water per pound of coal burned and the greater capacity of a boiler built within the space allowed. It suffices to use values of water evaporation, coal consumption and general boiler performance as obtained in experimental tests, and modify these " best performance " values by the knowledge of conditions obtaining in practical service.

The locomotive engine is distinct from the locomotive boiler, and when supplied with unlimited steam at constant pressure it has its own characteristics and maximum output both in tractive effort and horse power. Engines are of two general types, simple and compound, the latter being introduced in order to affect a saving in the large steam consumption inherent to non-condensing engine operation. The success of the compound locomotive is very much a matter of discussion among railroad men, but it seems to have found a permanent foothold upon easy-grade lines although its use is still open to serious question upon the heavy mountain-grade divisions. In general, the electric locomotive must compete with the compound steam locomotive on level divisions and the simple engine on heavy grade divisions, although the Mallet compound has lately been introduced with some success in this latter class of work.

The general shape of the steam locomotive characteristic is given in Fig. 1, which shows the relation between the speed and tractive effort of a simple consolidation locomotive designed for heavy freight service. Owing to clearances it is seldom that a locomotive can work at more than 90 per cent. of the theoretical full stroke, and hence the maximum tractive effort at starting with lever in the corner will not be much greater than 88 per cent. of the theoretical tractive effort available with gauge pressure in the cylinders. An inspection of Fig. 1 shows that the steam locomotive is limited as to maximum tractive effort by its engine design, and limited as to the speed at which this tractive effort is available by the capacity of the boiler to supply steam. Thus, assuming that the locomotive will give 88 per cent. of its theoretical tractive effort when starting, it is capable of providing but 80 per cent. tractive effort at a speed of 10.6 miles per hour (with the constants of the particular locomotive chosen for illustration) at which the boiler is giving its full output. Hence higher speeds can only be reached with a lesser cut off and a consequent reduction in mean effective pressure and tractive effort. Locomotive engines are generally designed to give their maximum tractive effort at 90 per cent. theoretical cut-off at a point corresponding to a coefficient of adhesion of approximately 22 per cent. of the weight upon the drivers; that is, at about slipping point of steam locomotives with good rail

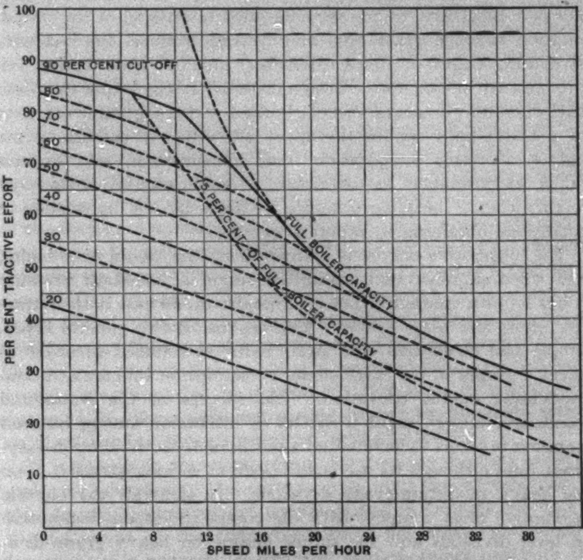

FIG. 1.—Typical steam locomotive characteristic (simple)

conditions. It is immediately evident therefore, that the tonnage rating of the locomotive on ruling grade must be so proportioned that the maximum tractive effort called for will be less than the available tractive effort of the locomotive in order to provide a small percentage, say 10 or 15 per cent., for possible starting under maximum grade and load conditions. In other words, as the steam locomotive is designed so that the maximum tractive effort is delivered at a point not greater than 22 per cent. of the weight upon the drivers, it is not possible to take advantage of possible abnormally good rail conditions (either natural or made abnormal by the use of sand) as the engine itself will fail to deliver any excess tractive effort thus made available with increased coefficient of adhesion.

On the other hand, the tractive effort of the electric locomotive is limited only by the adhesion between driving wheels and rail, and aside from some 15 per cent. greater adhesion possible with the uniform tractive effort provided by the electric locomotive, it is possible with this type of motive power to take momentary advantage of abnormally good rail conditions or to derive full benefit from the use of sand; indeed, tests have been taken with electric locomotives showing as high as 35 per cent. coefficient of adhesion between driving wheels and rail. This point is emphasized as with the greater tractive effort of the electric locomotive it becomes possible to give them a higher tonnage rating for the same weight upon the drivers than would be possible with steam locomotives operating over the same track profile.

There is a marked difference in the speed characteristics of the steam and electric locomotive, and indeed there is also a marked difference in the speed characteristics of different types of electric locomotives. Although this paper is not intended to enter into any discussion of the relative merits of different types of electric locomotives, there is so striking a difference in the several speed characteristics, each of which possess special advantages for certain operating conditions, that Fig. 2 has been prepared contrasting the characteristics of the steam locomotive and the direct-current gearless, alternating-current single-phase geared, and alternating-current three-phase geared electric locomotives. As all types of motive power share in common the fact of a certain critical speed beyond which full tractive effort cannot be maintained, the curves in Fig. 2 have been prepared on the basis of showing the relation between percentage of maximum tractive effort available at speeds higher than the critical speed, ordinates being tractive effort and abscissas percentage of critical speed to running speed.

A more familiar presentation is given in Fig. 3, showing a concrete case of a 22 by 30 steam locomotive of the simple type equipped with 57-inch drivers, contrasted with both an alternating-current geared and a direct-current gearless electric locomotive designed for the same tractive effort both maximum and running, but for a higher speed. The contrast of these different speed characteristics brings out sharply the small speed variation with different tractive efforts delivered by the electric locomotives, this small variation being even more marked in the case of the direct-current gearless than in the case of the alternating-current geared motor working at a lower iron saturation and thus affording a more sloping speed characteristic.

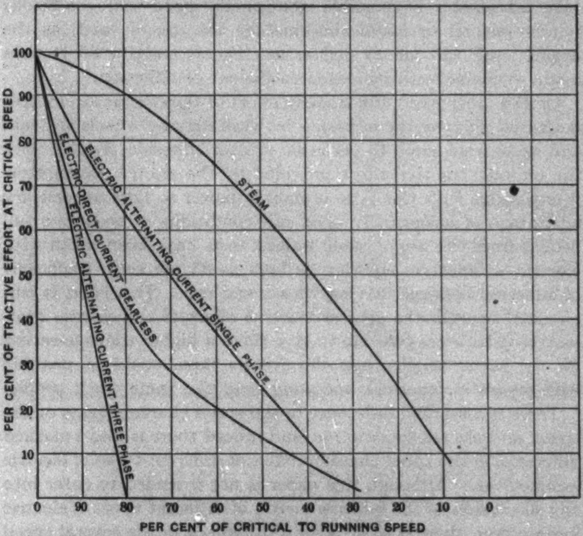

Fig. 2.—Typical characteristics of steam and electric locomotives

The steam locomotive chosen is typical of those in general use upon our mountain-grade divisions, the tonnage rating in operation of this particular locomotive being such as to call for a tractive effort of 25,600 pounds on *average* grade and 33,200 pounds on the maximum ruling grade occurring on a certain engine division, thus leaving a margin of 6,300 pounds above the demands of maximum tonnage on maximum ruling grade for starting the train from rest.

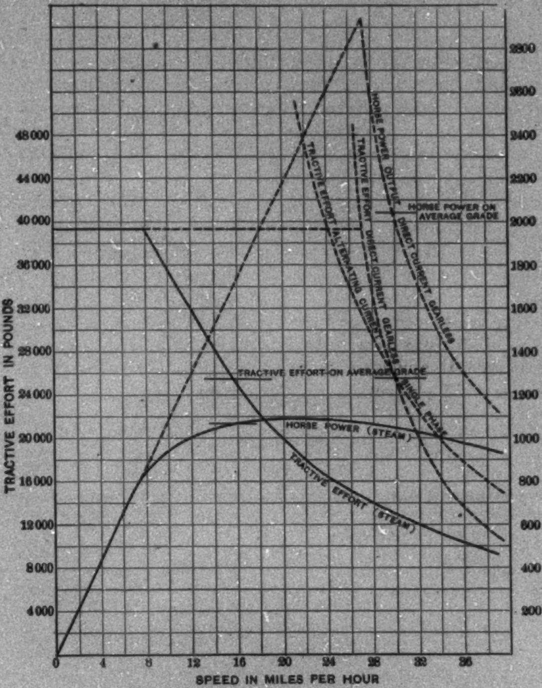

FIG. 3.—Steam and electric locomotive characteristics.

The maximum speed available at the different tractive efforts is a matter of boiler capacity, condition of boiler, quality of coal, and efficiency of fireman. The first of these factors, the boiler capacity, can be controlled by properly proportioning the design of the boiler to engine capacity, but there are three other factors which the locomotive manufacturer cannot control and two of these factors constitute sufficient cause to warrant a considerable reduction in the *theoretical rated capacity* of the boiler. Thus, referring to Fig. 1, such a locomotive in prime condition carefully fired with the best coal (approximating 14,000 B.t.u.'s) should be able to deliver full tractive effort at 10.6 miles per hour, but in practice it has been found that the average condition of boilers and the average firing provided by the none too conscientious or diligent fireman, cuts the *sustained* boiler output down to not much greater than 75 per cent. of its output under what must be considered exceptionally or momentary conditions, By sustained "output" is meant the output required while ascending the continuous up grades met with on our western mountain divisions, Though full boiler capacity may be attained for short periods, the average performance of all the locomotives on the division on the average up grade will show a marked reduction in capacity from the results obtained in a stationary test or single experimental test runs.

The locomotive characteristic in Fig. 3, has been prepared on the basis of 75 per cent. of the possible boiler capacity in the following manner:

GENERAL CONSTANTS OF SIMPLE CONSOLIDATION LOCOMOTIVE

Diameter of cylinders	22 in.
Length of stroke	30 "
Diameter of drivers	57 "
Heating surface	3397 sq. ft.
Total weight of locomotive	103.5 tons
Weight on drivers	93 "
Weight of tender	61.5 "
Total weight locomotive and tender	165 "

This particular locomotive has been chosen for illustration as it is the type in daily use on the mountain division of one of the largest Western roads.

Under the above conditions, the theoretical tractive effort is 49,500 pounds, of which 39,600 pounds is available at 90 per cent. cut-off. The contents of each cylinder is approximately 6.6 cu. ft. and with four cylinders of steam per revolution and with steam weighing 0.41 pounds per cu. ft. at 170 pounds cylinder pressure, each revolution requires 10.85 pounds steam. With 3397 sq. ft. of heating surface there is a possibility of evaporating six pounds of water per pound of coal when burning two pounds of coal per sq. ft. of heating surface, thus giving an available supply of 40,700 pounds of steam per hour when working boilers in prime condition at the full output resulting from perfect firing with good quality of coal. In practice, however, the available steam for sustained output would not be greater than 75 per cent. or 30,500 pounds per hour, thus giving full tractive effort at 46.8 revolutions of the drivers corresponding to 7.93 miles per hour on a 57-inch driver. The "critical speed" of the locomotive is therefore 7.93 miles per hour when working at 75 per cent. of full attainable boiler capacity, and the coal consumed under such circumstances will be 4,360 pounds per hour, corresponding to 1.28 pounds of coal burned per sq. ft. of heating surface, at which rate we would expect an evaporation of approximately seven pounds of water per pound of coal.

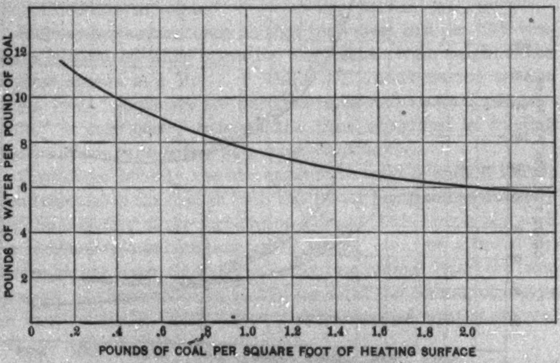

Fig. 4.—Rate of evaporation

What might be termed the "performance capacity" of a steam locomotive may be worked out from the speed and tractive effort characteristics given in Fig. 3, using as a basis the 1000 ton-miles trailing load moved per hour on a level or any gradient selected. The prevalence of 2.2 per cent. ruling grade on many of our Western roads perhaps justifies the selection of that figure for demonstration purposes; and the coal consumed, crew wages, and maintenance charges, may all be worked out from the basis of continuous operation per 1000 ton-miles trailing load on 2.2 per cent. grade, these results being shown in Fig. 5.

Certain assumptions are necessary and are as follows:

Cost of coal		$3.00 per 2000 lb.
Engineer	wages per hour	$0.50
Fireman	" " "	0.35
Conductor	" " "	0.40
Three brakemen	" " "	0.90
Total crew		2.15

Average mileage per locomotive per year, 36,500.

Total maintenance including round house charges, $5,000.00.

Maintenance per locomotive mile actually run, 13.7 cents.

General locomotive constants are the same as previously given.

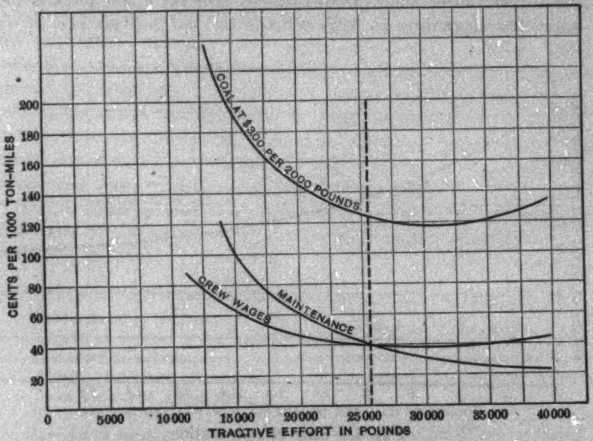

Fig. 5.—Performance capacity steam locomotive (simple) grade 2.2% (up)

Having broadly outlined the performance characteristics of the simple consolidation engine frequently met with in heavy grade operation, it becomes necessary so to proportion the constants of the electric locomotive, assumed to replace it, so as to gain the greatest benefit from the different inherent characteristics of the latter type of motive power.

Referring to Fig. 2, it is evident that with the small speed variation of the electric locomotive, and due to the fact that its motive power is separate from its unlimited source of power generation, it is possible to consider radical changes in the method of moving freight, more especially on mountain-grade divisions.

It has become a partly accepted fact that the electric locomotive characteristic should be so proportioned as to enable it to operate trains at a high rate of speed on level track and at a much slower speed on grades, in fact conforming with present steam practice in this respect. The writer would again point out that steam railroading to-day is in reality steam locomotive practice in that the speed possibilities of different track divisions are restricted to a large extent by the limitations of the steam locomotive. In other words, the only reason why it is common practice to run at very low speeds on mountain-grade divisions instead of continuing the high speeds in vogue on more level portions, is because a steam locomotive cannot be built powerful enough to supply the heavy tractive effort required at any higher speeds than those now in vogue.

Railway economies teach us that the lowest cost per 1000 ton-miles is obtained when operating the greatest train weight at the highest speeds, and Mr. J. J. Hill's well known saying to the effect that " Expenses are per train-mile and receipts per ton-mile ", is only partly true, as the time consumed in hauling the train one mile enters as a most vital factor.

Considered broadly, the one expense in train operation that is fundamental is the cost of fuel, this factor being influenced only by the economy of the fuel-burning plant. Other expenses, such as locomotive maintenance, crew wages, etc., are affected entirely by the method of operation, and no radical departure from present methods is to be looked for until the coming of a type of motive power which offers possibilities not equally enjoyed by the steam locomotive.

This point is further illustrated by reference to the operating sheet of one of our greatest Western roads using the simple consolidation locomotive previously described.

SPEED RELATIONS. ROAD " A " MOUNTAIN DIVISION

	UP GRADE	DOWN GRADE
Schedule speed................	7.35 miles per hr.	12.5 miles per hr.
Average speed while running....	12.1 " " "	20.0 " " "
Number stops per mile.........	0.177 " " "	0.149 " " "

The average schedule speed of a number of trains, including all layovers due to the despatcher or failure of motive power, as obtaining on another mountain division of a different road, showed values as low as 6.7 miles per hour up grade. In general it may be stated that the freight movement over mountain divisions is effected at very low schedule speeds, and the cause is evident from an inspection of the steam locomotive characteristic. Except for the fact that curves are usually of shorter radius on heavy grades than on levels, there is no reason for the slower speed of trains, provided a type of motive power is available that is capable of supplying great draw-bar pulls at high speeds. It is just this characteristic which the electric locomotive possesses to an almost unlimited extent, and such locomotives can be built which are even more powerful and operate at higher speed than can be utilized at present.

For example, the simple consolidation locomotive considered is capable of sustaining a tractive effort of 25,600 lb. at a maximum speed of 15.4 miles per hour, and weighs 165 tons with tender, while a single New York Central electric locomotive of the 6000 type is capable of delivering the same tractive effort at approximately 37 miles per hour, and the weight is only 100 tons. The Central locomotive is of course designed for moderate speed passenger service and could not be run continuously at such a large output, but it is cited only as an example of a well-known electric locomotive having an enormous horse power capacity, although in this respect it is but the forerunner of other electric locomotives having still greater outputs. Owing to the fact that such units may be run in groups of two or more and still be perfectly under the control of a single operator, the advantage of very large single units is somewhat modified, and the introduction of the electric locomotive may also introduce new ideas as to the size and construction of single hauling units.

The electric locomotive may be equipped with motors of several different types each having characteristics best qualifying it for certain classes of work. Fig. 6 and Fig. 7 illustrate the usual speed, torque, and efficiency curves of two typical motors, the direct-current gearless and the alternating-current single-phase geared type. The type of motor to be adopted is a matter requiring full local knowledge of the conditions obtaining in each individual instance before a proper selection can be made. All three of the available motors—direct current; alternating current single-phase; and alternating current three-phase, possess the one needed characteristic of great output per pound and hence the arguments advanced for the substitution of the electric for the steam locomotive are general in character and do not apply strictly to locomotives equipped with any one type of motor to the exclusion of all others. As the direct-current gearless motor can be built in the largest sizes, is the best understood, and is in successful operation upon a very important division of one of the largest steam roads, it is here chosen as the equipment of a typical electric locomotive.

The large output, 840 h.p. for one hour and 400 h.p. continuous, shown in Fig. 6, illustrates what can be accomplished with this type of motor. The output of the complete locomotive is dependent upon the number of motors permitted with the construction adopted. Thus, such a four-motor equipment is capable of delivering a tractive effort of 56,800 lb. at a speed of 23 miles per hour approximate (depending upon the voltage) while the efficiency of conversion at this output would be 87 per cent., rising to a maximum of 93 per cent. at higher speeds and lower tractive effort. Another form of construction, say one similar to that employed in the largest Mallet compound. would permit the use of two four-axle articulated trucks, providing an equipment of eight motors and an output of 113,600 lb, at a speed of 23 miles per hour.

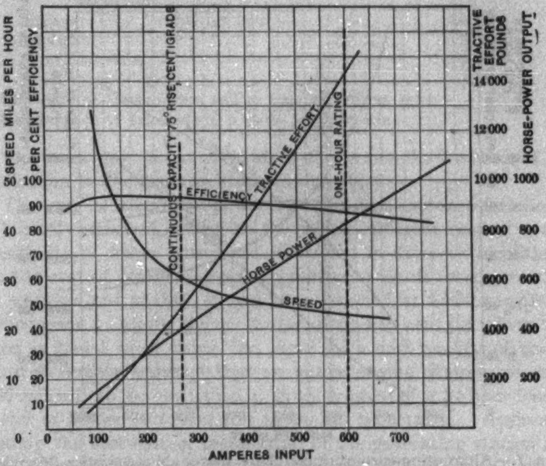

Fig. 6.—Direct-current gearless motor characteristics, 1200 volts

The same motors could readily be rewound to give the same tractive effort at *considerably increased speeds* if desired, without materially increasing the internal losses of conversion. Bearing fully in mind the fact that a single operator has this enormous energy under perfect control, and that such a locomotive could do the work of two or more Mallet compounds and several locomotives of the simple consolidation type, and it becomes evident that in the electric locomotive there are tremendous possibilities of improving present methods of railway operation as now conducted with the steam locomotive. Carrying the thought a step further and appreciating that several such electric locomotive units may be operated in a group forming a combined unit, it becomes evident that in the electric locomotive we have a type of motive power capable of furnishing any output in tractive effort and speed that present or future operating conditions may demand.

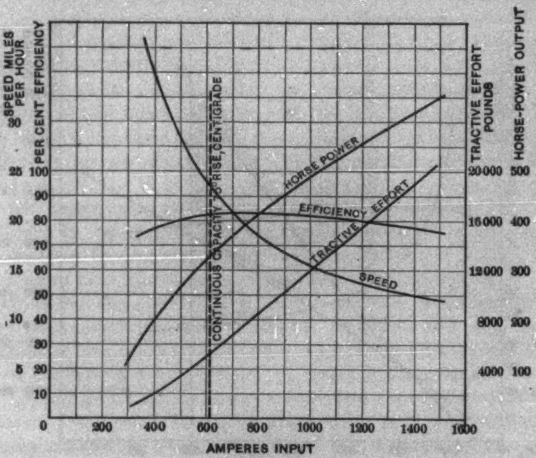

Fig. 7.—Alternating-current single-phase motor characteristics, 25 cycles, 375 volts

Returning to the direct comparison of the simple consolidation and electric locomotive, Fig. 3, was plotted on the basis of a speed of 30 miles per hour for the electric and 15.4 miles per hour for the steam locomotive, giving in each instance a tractive effort of 25,600 lb. at the rim of the drivers. Though the electric locomotive could very readily be designed to give the same tractive effort at a higher speed, 30 miles per hour was assumed as the highest speed permissible due to the alignment of the track on heavy grades.

To plot a performance capacity curve for the electric locomotive, certain further assumptions are necessary.

Type of equipment, direct-current gearless motors.

Weight of total locomotive	125 tons
" on drivers	100 "
Engineer wages per hour	$0.50
Conductor " " "	0.40
Three brakemen " " "	0.90
Total wages of crew	1.80

Efficiency of transmission rail to bus-bar, 70 per cent.
Maintenance of locomotive, 5 cents per mile run.

The train crew is so divided as to permit the location of a brakeman in the engineer's operating cab.

The cost of electrical power must in this instance be most arbitrarily assumed, owing to the widely different cost of coal, possibility of water power, etc., obtaining in different localities. As the cost of coal for steam locomotives will also vary greatly as to price and quality, it has been assumed at $3.00 per 2000 pounds, and a cost for electric power of one-half cent per kilowatt-hour is based upon using the same price and quality of coal. As it is further assumed that an entire engine division of say 150 miles is to be electrified, it gives promise of a 24-hour load-factor of 50 per cent. and this figure has been taken. Approximating the first cost of installation of the generating station at $100.00 per kilowatt, and allowing ten per cent. per year for interest and other fixed charges, the cost of power is brought up to possibly $0.0075 per kilowatt-hour at the station bus-bar. Other conditions obtaining will in a given instance modify the figures arrived at, but for purposes of demonstration $0.0075 is a conservative estimate, and such a figure is needed to compare the cost of power with the fuel item in steam-locomotive performance.

The effect of increased speed on cost of operation is clearly shown by comparing the performance capacity curves of the steam and electric locomotives, Figs. 5 and 9.

It will be observed that the reduction in the operating expenses is effected in the two items of crew wages and maintenance of locomotives, and that the cost of fuel remains practically unchanged. This is as it should be, as the cost of fuel in the case of steam locomotives or power with electric locomotives is the only fundamentally necessary expense in train movement. Overcoming train friction and raising a train up grade against gravity represents useful work performed, and this work is accomplished at an expenditure of approximately four pounds of coal per horse power-hour at the drivers with simple engines and 2.66 pounds of coal per horse power-hour at the drivers with electric locomotives, including all intervening losses between rail and

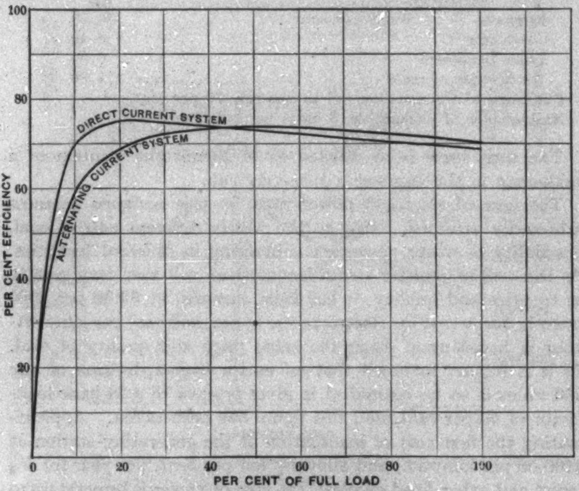

Fig. 8.—Efficiency of distribution generator to rail

generating station bus-bar. The speed at which this work is performed, therefore, does not affect the cost of fuel or power, it being assumed that the motive power for the various speeds is so proportioned as to operate at the point of greatest economy.

Thus with coal at $3.00 per 2000 pounds in each case, the steam locomotive can generate a horse power at the drivers at an expenditure of $0.006 as against $0.0039 for fuel alone with the electric. The two figures are not directly comparable, as to the cost of fuel for steam locomotive operation must be added the extra cost of hauling, which on grade divisions may constitute a large percentage of its original cost; and the waste incident to handling and storing in many bunkers along the tracks. In addition, there is a considerable quantity of coal burned under the boilers of steam locomotives standing idle or coasting down grades, which will be shown later, may equal ten per cent. of the total consumption in main line freight movement and much more in the case of helpers and switching engines. If, therefore, coal be delivered at the engine division terminal

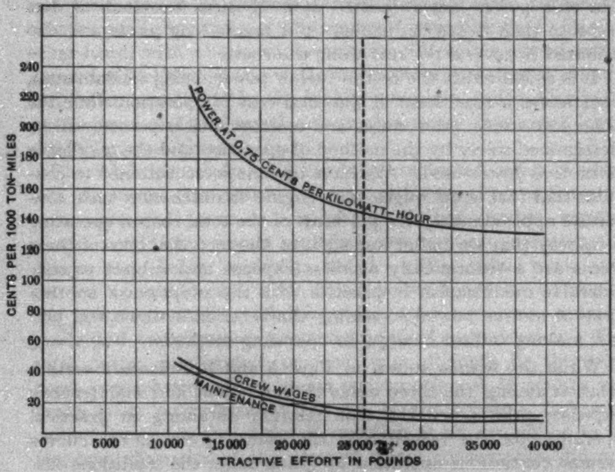

FIG. 9.—Performance capacity electric locomotive (Direct-current gearless) grade 2.2% (up)

at $3.00 per ton, the actual cost on the tender will be considerably in excess of this figure, and due allowance must also be made for the coal wasted, burned or otherwise, and not producing useful brake horse power-hours at the rim of the drivers.

In the electric system also, besides the allowance made in distribution losses in arriving at 2.66 pounds coal burned per horse power-hour at the rim of the drivers, there will be an additional charge for labor and fixed expenses incident to power-house operation and first cost. The electric system, however, is not restricted to the use of high-grade fuel and coal of an inferior quality, and much lower cost, such as lignite, can be utilized, besides the large opportunities for cheap power presented by the water powers generally available on mountain divisions.

The saving or deficit in the power item with electric as contrasted with the fuel item of steam locomotive operation must, therefore, be largely determined by the local factors entering into the case. A common cost of $3.00 per 2000 pounds for coal is taken in this discussion; it is rather favorable than otherwise to steam locomotive operation, as coal can be dropped into the bin of a power house located at a division terminal at less expense than it can be hauled up a severe long grade and distributed in several pockets along the route.

It is evident that the cost of fuel or power, being fundamental, constitutes a fixed item in the total cost of operation while the other two items, crew wages and maintenance expenses, will be determined solely by the method of operation and the excellence of motive power used. We have become so accustomed to consider that fuel, crew wages, and engine maintenance each constitute approximately ten per cent. of the total cost of operating a railway that we rather lose sight of the fact that two of these items are a theoretically needless expense and subject to considerable modification in practice with the adoption of another type of motive power possessing characteristics which will permit making radical changes in operating methods.

While the figures shown in Figs. 5 and 9 indicate a certain relation among the three items of fuel, crew, and maintenance expense, this is not the true relation obtaining in practical operation for the reason that the values given in the curves assume continuous operation up grade under the conditions outlined. Unfortunately, train crews must be paid full value per mile whether the mile be up grade or down, and with steam locomotives there is also a considerable loss in fuel resulting from engines standing or running light which must be also taken into account; hence it becomes necessary to modify the figures arrived at, and for this purpose certain references must be made to current railroad practice on mountain-grade divisions in order to arrive at the proper tonnage relations, schedule speeds, etc., obtaining in up-grade and down-grade operation.

Previous figures have been given showing that the schedule speed on several mountain divisions is approximately 50 per cent. of the average running speed and this figure is assumed in the following statement of cost of operating 1000 ton-miles with steam locomotives, averaging the cost of up- and down-grade running. Owing to the higher schedule speed of electrically operated trains, resulting in fewer meeting points with the same tonnage handled, and due to the absence of forced stops to take on fuel and water, etc., it is assumed that with electric motive power the schedule speed may be 60 per cent. of the running speed.

With the electric locomotive standing, or coasting down grade, there is no demand whatever made upon the generating station, and hence the only expense carried through these periods is that for train crew and a certain amount for maintenance. On the other hand, with the steam locomotive there is a considerable amount of fuel burned and water wasted when standing at sidings and when coasting. In the case of mountain railroading with its frequent and prolonged delays, this waste may reach considerable proportions.

The following results of a carefully conducted series of tests will illustrate this point. Two test locomotives and trains were operated over a mountain division under regular service conditions—steam and fuel consumption, duration of delays, etc., being carefully noted. The total work expended up grade was 5700 horse power-hours at the rim of the drivers including allowance for 1.54 per cent. average grade and seven pounds per ton track and curve friction. The total water evaporated on the trip divided by the total horse power-hours gave a steam consumption of 36 pounds per brake horse power-hour at the rim of the drivers. Indicator cards taken upon the engine in question at all cut-offs up to 90 per cent. showed that the greatest steam consumption did not exceed 32 pounds per indicated horse power-hour, or 35.5 pounds per brake horse power-hour, allowing ten per cent. internal engine friction. Values as low as 23 pounds of steam per indicated horse power-hour or 25.5 pounds per brake horse power-hour were recorded for the average cut-off of 40 to 50 per cent. used throughout the run. A third and fourth series of tests conducted up the same grade gave similar results, except that the values were slightly higher than those quoted, showing that there was a considerable loss of water unaccounted for by indicator cards and useful work performed.

Operating down grade, it was necessary to accomplish 1110 horse power-hours on account of the somewhat broken profile, and again the water consumption showed on two trips 57.7 pounds of steam per brake horse power-hour, and on two subsequent trips 66.5 pounds, values entirely unaccountable on the basis of useful work performed.

During all tests the usual service delays occurred, and as the traffic on the road in question was very much congested, these delays constituted a considerable proportion of the total elapsed time. In fact during the runs up grade the trains were in motion but 66 per cent. of the total elapsed time, and down grade the trains were in motion from 52 per cent. down to 40 per cent. of the total elapsed time. As these delays were frequent and undetermined, it was necessary to maintain full steam pressure while waiting for the momentarily expected release from the block, hence the waste of fuel and water was considerable. Averaging this waste at 400 pounds per hour, at which low rate of consumption the water evaporation would approximate ten pounds of water per pound of coal burned, or 4000 pounds of water evaporated per hour, and reducing the total water consumption measured by the waste losses thus obtained, the steam consumption in eight different tests up and down grade ranged 34.7 pounds, 32.4 pounds, 28.1 pounds and 25.3 pounds, etc., water per brake horse power-hour. These values are fairly commensurate with results of indicator cards taken, and, with the type of engine used and under the operating conditions obtaining, an allowance of 400 pounds of coal stand-by losses per idle locomotive-hour seemed not too great a value to allow, and this figure has been taken in subsequent calculations.

Locomotive performance capacity curves may therefore be plotted which will show approximately the true relation between the several items of fuel, crew wages, and motive power maintenance, by adhering to the following assumptions:

Ratio schedule to running speed up-grade steam locomotive,	50 per cent.
" " " " " electric "	60 per cent.
Schedule speed down-grade steam	15 miles per hour.
" " " " electric	18 miles per hour.
Cost of coal	$3.00 per 2000 lb.
" " electric power	0.0075 per kw-hr.
Efficiency of distribution	70 per cent.
Crew wages per hour steam	$2.15
" " " " electric	$1.80
Maintenance locomotive steam	$0.137 per mile.
" " electric	$0.05 per mile.
Fuel waste per idle hour steam	400 lb.

An inspection of the performance curves shows that in practical operation the fuel expense approaches more nearly to the value of the other items considered, instead of being greatly in excess of them as indicated in the theoretical performance curves, Figs. 5 and 9, showing up-grade operation only. For operation on lesser grades than 2.2 per cent., all items are reduced and the total and subdivided comparative costs are given in the following table and in Fig. 11.

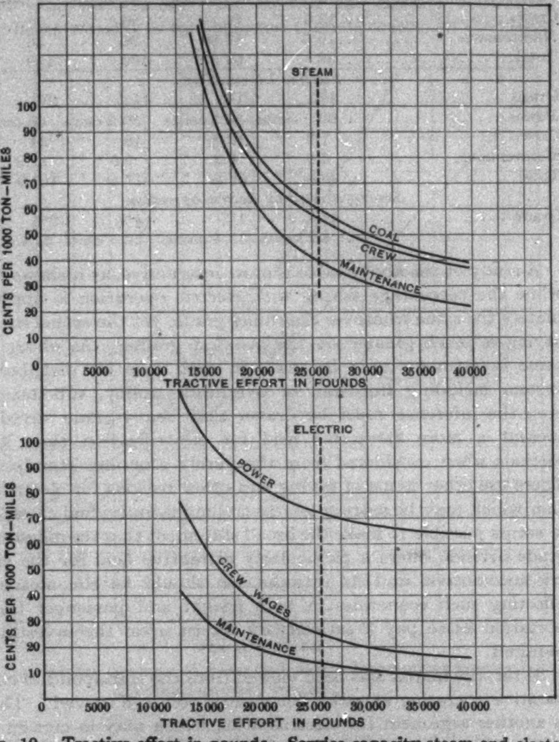

FIG. 10.—**Tractive effort in pounds. Service capacity** steam and electric locomotives average of up and down 2.2% grade

COMPARATIVE OPERATING EXPENSES PER 1000 TON-MILES STEAM (SIMPLE) AND ELECTRIC LOCOMOTIVES

AVERAGE OF UP- AND DOWN-GRADE OPERATION

Steam Locomotives

Grade	½%	1%	1½%	2%
Coal	15 cents.	25.5 cents	38 cents.	53 cents.
Crew	13.5 "	24 "	36 "	50 "
Maintenance	10.5 "	17.8 "	26 "	36 "
Total	39 "	67.3 "	100 "	139 "

Electric Locomotives

Grade	½%	1%	1½%	2%
Power	20 cents	35.5 cents	50.5 cents	66 cents.
Crew	7.2 "	12.2 "	18 "	24 "
Maintenance	3.6 "	6.2 "	9.0 "	11.9 "
Total	30.8 "	53.9 "	77.5 "	101.9 "

Saving effected by electric operation

Grade	½%	1%	1½%	2%
	8.2 cents	13.4 cents	22.5 cents	37.1 cents

A study of the above table is most instructive, as it shows that while the percentage saving with electric operation is approximately the same whatever the ruling grade, yet the actual money saving is much greater on the heaviest grades. As about the same investment must be made in each case for distribution system including third-rail or overhead trolley, sub-stations, etc., the inference must be drawn that heavy-grade divisions present a more attractive field for electrification than level sections when considered from the purely economic standpoint. There are other items of saving and other reasons for electrification which may be more or less controlling in individual cases, but it seems possible to make the broad statement that the mountain-grade division offers a particularly attractive field for the electric locomotive, and its introduction should be the means of affecting such economies in both freight and passenger transportation as to pay a satisfactory return upon the investment required.

So far, the matter has been viewed from the standpoint of comparative operating expenses for a given tonnage moved. There is another argument for electrification which may in certain instances be of a much more controlling nature. Most of our mountain roads are single track and transcontinental tonnage has so increased as seriously to congest these mountain divisions. The heavy trains of the plains, weighing 2000 to 3000 tons, must be split up into units of about 1000 tons in order that the present steam engines, operating double and even triple, may haul them over the heaviest grades. The slow speed obtainable makes the number of trains on a mountain division large, the meeting points frequent, and hence, however good the despatching system employed, there will of necessity be a considerable amount of lost time introduced. Add to this the failures of motive power being worked to its limit, and there is reason for the claim that the tonnage capacity of the division will be greatly increased by the introduction of electrically hauled trains.

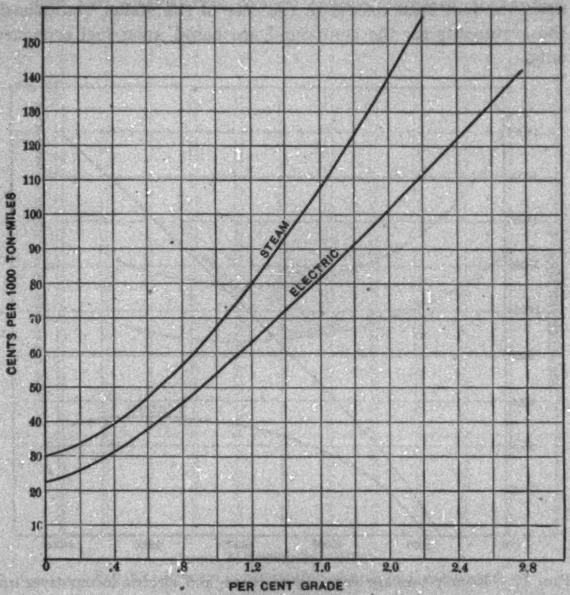

Fig. 11.—Service capacity of steam and electric locomotives average both directions and any gradient

Lest the writer be accused of unfairness in selecting the simple engine for comparison, it is proper to touch upon the economies effected with the use of the compound locomotive and also by the introduction of such coal-saving devices as superheaters and feed-water heaters.

Reference to Fig. 13, shows a saving in water consumption per horse power of approximately 20 per cent. with the compound locomotive, but in spite of this generally accepted saving the simple locomotive still rules the mountain division after repeated trials of the compound. Not being an ardent supporter of either type of locomotive, the writer leaves the battle of the simple and compound to their enthusiasts, commenting only upon the fact that, except in the case of the Mallet compound, the arguments for the compound are based upon fuel economy only.

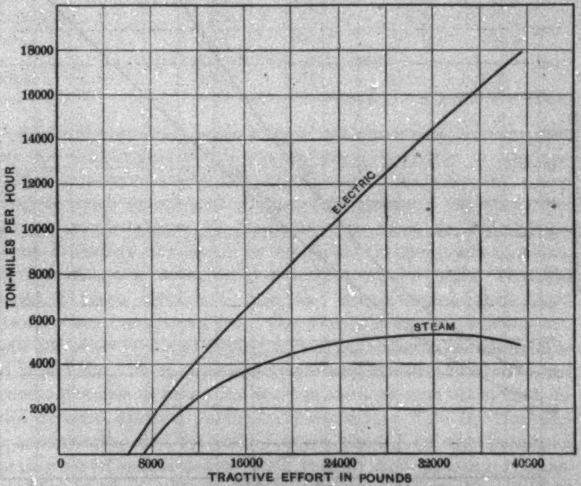

FIG. 12.—Hourly tonnage capacity of steam and electric locomotives up 2.2% gradient

The latest Mallet compound, weighing 413,000 pounds, is the largest steam locomotive yet built, and is of particular interest owing to the enormous boiler which such a construction permits. With a total heating surface of 5300 sq. ft. we should expect an evaporation of 63,600 pounds of water for a short period and possibly 48,000 pounds water continuously. With a possible evaporation of six pounds of water per pound of coal, this would necessitate the burning of 8,000 pounds of coal per hour, requiring the best efforts of two firemen if maintained for several hours. Assuming a steam consumption of 22 pounds per brake horse power-hour, such a locomotive should give a sustained output of 2180 horse power at the rim of the drivers, and this with a weight with tender of approximately 300 tons, or three times the weight of an electric locomotive of the New York Central 6000 type giving the same horse-power output.

The two locomotives are, of course, designed for entirely dissimilar classes of work; but it is not unfair to compare them on a horse-power basis as it is the huge boiler of the Mallet that is remarkable, and upon this basis the selling price of the two machines is approximately the same.

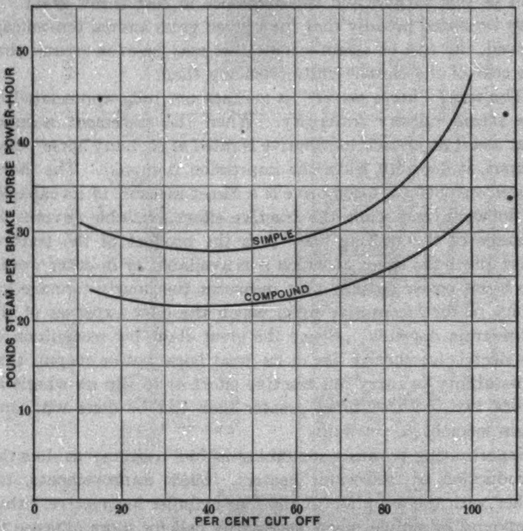

FIG. 13.—Steam consumption simple and compound

The comparative cost of electric and steam locomotives is generally considered as very favorable to the steam units, but reversing the usual methods and comparing the cost of the electric with that of the steam locomotive or locomotives required to replace it, may reverse the relations. The electric locomotive requires no more than casual inspection, can be side-tracked indefinitely and still be ready for instant operation at full capacity, can run 24 hours without a stop, if necessary, and all these advantages and others offers a guarantee for a much greater annual mileage than is possible with its steam competitor. Then, too, compare the cost of a group of steam locomotives (no single unit could be designed to give the output) capable of delivering even 4000 h.p. continuously with a single electric unit of this output, and the difference in cost is not great. It may be stated broadly that for a given gross annual ton-mileage moved, the cost of steam locomotives may be even greater than the cost of the electric units replacing them.

The term " horse power " is perhaps not fully appreciated by the steam railway fraternity. When the statement is made that a certain electric locomotive is rated at so many horse power output, it does not leave the impression it should. The horse power output of a locomotive is a direct measure of its capacity to do work, and while the tractive effort available governs the tonnage of the trailing load, it is the product of the tractive effort times the speed at which it is available, or in other words, the horse power output, that measures the hourly tonnage capacity of the locomotive upon which the crew expenses of the entire train depends. Hence the great claim for recognition of the electric locomotive lies in its great horse power output, that is, its ability to carry full tractive effort or to slip its wheels at speeds two or three times greater than can be done with any steam locomotive yet built.

Superheating promises something in fuel economy as does the introduction of feed-water heaters. Such improvements, together with the adoption of the four-cylinder locomotive, either compound or simple, must necessarily call for more expense to maintain and less reliability in operation. In fact, superheating in stationary boiler plants has given much trouble, and excessive superheating has not been a complete success even when used with turbines, with which superheating has given the best results. Judged from stationary engine practice, it seems fair to assume that the amount of superheat in locomotive practice must be moderate and result in small benefits to be secured.

The feed-water heater is also a coal-saving device and should prove to be worth its added complication as soon as it is commercially developed.

's against the reduction in fuel expenses promised by the use

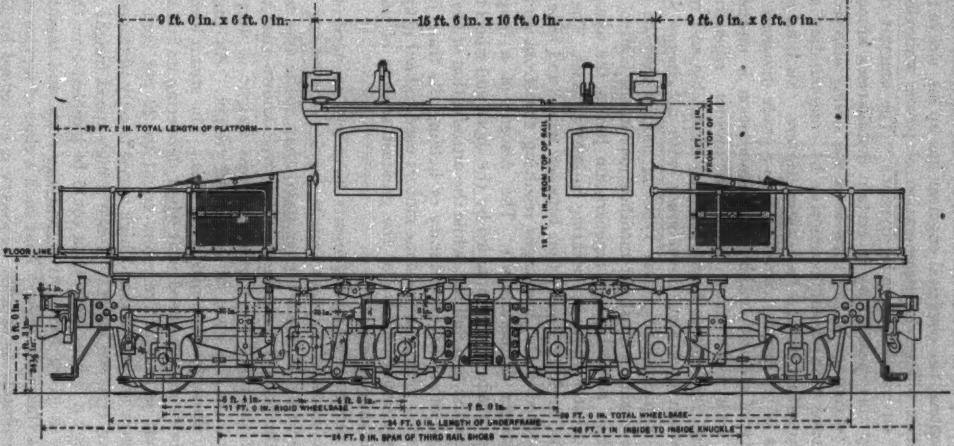
9 ft. 0 in. x 6 ft. 0 in.
15 ft. 6 in. x 10 ft. 0 in.
9 ft. 0 in. x 6 ft. 0 in.
39 FT. 2 IN. TOTAL LENGTH OF PLATFORM
13 FT. 1 IN. FROM TOP OF RAIL
12 FT. 11 IN. FROM TOP OF RAIL
FLOOR LINE
6 ft. 0 in.
1 in.
6 ft. 4 in.
4 ft. 8 in.
11 FT. 0 IN. RIGID WHEELBASE
7 ft. 0 in.
29 FT. 0 IN. TOTAL WHEELBASE
34 FT. 0 IN. LENGTH OF UNDERFRAME
40 FT. 8 IN. INSIDE TO INSIDE KNUCKLE
24 FT. 0 IN. SPAN OF THIRD RAIL SHOES

FIG. 14.—Typical electric freight locomotive 2-4-4-2 type

of the compound locomotive fitted with superheaters and feed-water heaters, the electrical engineer has up his sleeve the great possibilities offered by regeneration of power while electrically braking on mountain-grade divisions. The amount of power saved by this means may in certain installations amount to as great a percentage of the total as is the saving affected in coal expenditure with steam locomotive by compounding and providing superheaters and feed-water heaters. Such an electrical saving is of course restricted to heavy-grade divisions, but the feasibility of electric braking by regeneration is unquestioned. Indeed with three-phase induction motors regeneration is automatic, the motors being perfectly reversible and returning energy when operating down grade with no change whatever in their connections. Other types of motors may be adapted for regeneration with slight modifications in the control system.

The chief advantage of regeneration lies in the assurance it offers of greater safety in operating on heavy grades. The present method of braking, by friction between wheel and shoe, results in overheated parts, breakages resulting therefrom and consequent danger of derailment. The descent of a long heavy mountain grade is accompanied by the shoes and wheel rims becoming heated to a dull red, while the introduction of the electric locomotive offers an opportunity of holding the train in whole or in part by means of the same motors used to haul it up grade, and thus eliminating one of the greatest sources of danger in mountain railroading.

All of our railway managements have felt the need of establishing a so-called express freight service comprising a light train operating at much higher speed than is the case with the bulk of the freight movement. It is well known that the cost per 1000 ton-miles for moving express freight is very much higher than in the case of low-speed freight. An inspection of Fig. 3, illustrates the reason for this. The steam locomotive is essentially a slow-speed unit when delivering its full tractive effort; that is, a tractive effort equal to 22 per cent. of the weight upon the drivers, and high speed is only obtained at the sacrifice of tractive effort. Hence a high-speed freight train is of necessity a lighter train than could be handled over the same profile by a given locomotive, and the crew and maintenance expense is therefore large. That such a class of service is nevertheless profitable or at least necessary is evidenced by the continuance of the practice and the proposed introduction of elec-

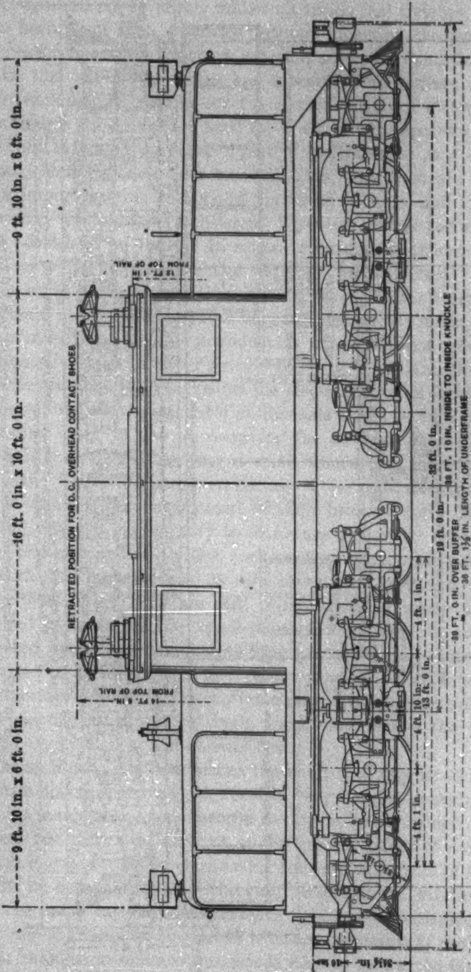
9 ft. 10 in. x 6 ft. 0 in.
16 ft. 0 in. x 10 ft. 0 in.
9 ft. 10 in. x 6 ft. 0 in.
12 FT. 1 IN. FROM TOP OF RAIL
14 FT. 6 IN. FROM TOP OF RAIL
RETRACTED POSITION FOR D.C. OVERHEAD CONTACT SHOES
4 ft. 1 in.
4 ft. 10 in.
4 ft. 1 in.
13 ft. 0 in.
19 ft. 0 in.
33 ft. 0 in.
36 FT. 10 IN. INSIDE TO INSIDE KNUCKLE
39 FT. 0 IN. OVER BUFFER
36 FT. 1½ IN. LENGTH OF UNDERFRAME
10 in.
31½ in.

FIG. 15.—Typical high-speed passenger electric locomotive

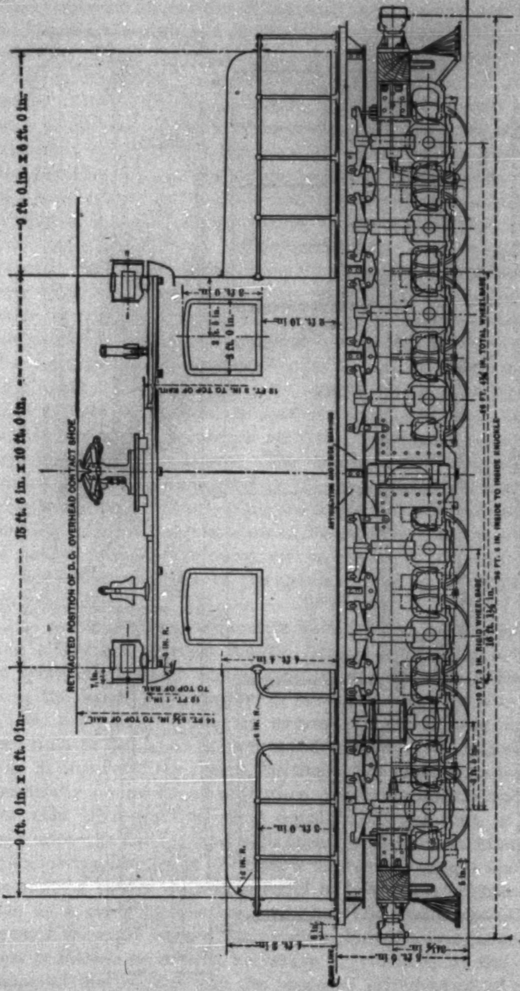
9 ft. 0 in. x 6 ft. 0 in.
15 ft. 6 in. x 10 ft. 0 in.
9 ft. 0 in. x 6 ft. 0 in.
RETRACTED POSITION OF D.C. OVERHEAD CONTACT SHOE
3 ft. 6 in.
3 ft. 0 in.
2 ft. 10 in.
4 ft. 4 in.
3 ft. 0 in.
ARTICULATION AND SIDE BEARINGS
RIGID WHEELBASE
TOTAL WHEELBASE
INSIDE TO INSIDE KNUCKLE
TO TOP OF RAIL
Base Line

FIG. 16.—Typical electric locomotive heavy freight 0-8-8-0 type

tric locomotives, in effect, makes all trains fast freights, gaining the benefits of such a service without incurring the penalty of increased operating expenses inherent to steam operation.

In this paper the writer has attempted to outline some of the fundamental reasons for the electrification of steam roads; the figures submitted are used for illustrative purposes only and are not intended as being directly applicable to any concrete case. Many of the points touched upon, such as steam locomotive improvements, compound versus the simple, and the comparative advantages of different types of electric locomotives, etc., could all be treated in separate papers by themselves, so replete with interest are the different points raised. Rather than befog the main question at issue, which is the electrification of steam roads, detailed proof of many statements made has not been attempted, as the introduction of such proof would unnecessarily extend a paper already too long. Nor does the writer believe that the time is ripe for the electrification of steam roads at large; indeed, the electrical enthusiasts would be hard put to it if called upon to show reason for the electrification of many branch steam lines carrying a small tonnage at infrequent intervals. There are, however, certain divisions of our steam railways which, either on account of their broken profile or heavy traffic, offer an opportunity to introduce a superior type of motive power which will effect such economies in operation as to provide adequate return on the investment required for the electrification. There are still other divisions where a much desired increase in the track-tonnage capacity can only be effected by double tracking so long as the steam locomotive is adhered to as the type of motive power used. Double tracking a mountain-grade division is often a matter of enormous expense, and electrification of the single track may relieve the present traffic congestion at a moderate cost.

On mountain-grade divisions the subject of regeneration with electric locomotives should receive very careful consideration, not so much on account of the saving in power which it may effect, but rather on account of the greater safety of operation which it guarantees by eliminating the serious defects of holding trains on heavy grades by wheel and shoe friction. Finally, there are the many incidental advantages to be gained with electrification which cannot be predicted with any accuracy, as they result from changes in operating methods sure to follow the introduction of a type of motive power not subject to the service limitations of the steam locomotive. No attempt has been made even to approximate the saving effected in engine supplies, roundhouse expenses, elimination of water supply with its often attendent expensive purifying outfit, and the many items incident to steam locomotive operation. These items are incidental and seldom assume an importance sufficiently great to class them as fundamental, though the difficulty of procuring good water, even with purifying plants, may approach very closely to being a controlling factor in certain cases.

The freight-car shortage problem itself is a very serious one at certain times of the year on some roads, and as the total freight-car mileage can be increased with the higher speeds provided with electric locomotives, it should result in the saving of a considerable expense now incurred for rental of foreign cars, or even increase the gross receipts by the movement of tonnage which more available cars would make possible.

The subject of the electrification of steam roads is, therefore, a very broad one, and while this paper has been devoted largely to a discussion of operating expenses as affected by the different characteristics of the two types of locomotives, it has been done to illustrate the advantages resulting from increased locomotive capacity. The keynote of electrification is *capacity;* by approaching the problem from this standpoint only can full benefits be obtained.

DISCUSSION ON "COMPARATIVE PERFORMANCE OF STEAM AND ELECTRIC LOCOMOTIVES", AT NEW YORK, NOVEMBER 8, 1907.

William J. Wilgus: Instead of apologizing for adding to the number of papers on the electrification of steam railroads, the author should feel entitled to congratulations for calling attention to many of the advantages of the electric locomotive that have heretofore escaped analysis. In my judgment the cause is injured rather than benefited by arguments for the wholesale application of electricity to steam railroads, and it is pleasing to note the increasing tendency in our technical societies to sane discussions that will really enlighten the railroad officer anxious to be in the van of progress.

Unquestionably, electricity in heavy traction work has come to stay. As the author states, until now the reasons that have lead to the principal changes of motive power are entirely apart from questions of economy in operation. Conservative advocates of heavy electric traction, while urging its self-evident advantages in the abolition of the products of combustion in tunnels and cities, the increasing of terminal capacities, and opportunities for growth of traffic, have refrained from dwelling too strongly on saving money. They have been contented with the belief that more money could be made. The burden of additional interest charges, taxes, maintenance and depreciation attendant upon the substitution of electricity for the old form of motive power has very properly caused the careful engineer to pause in admitting even to himself that in addition to increased capacity to handle traffic, there might be a net saving in cost of operation. This cautiousness has sprung from the absence, until recently, of any actual data on the cost of heavy electric traction operation.

The pioneer electrical installation in heavy trunk-line service, on the New York Central & Hudson River Railroad, has now been in complete and successful operation since July 1, 1907, the gradual change from steam power having commenced in December, 1906. The working side by side of both kinds of motive power has given unsurpassed opportunities for the observation of their comparative capacity and efficiency. The results are even more gratifying than were expected; and substantiate many of the author's claims of superior capacity of electric equipment, although the conditions differ widely from those that he has assumed.

At this point it may be well to venture a word of caution on the subject of costs. Comparisons are worthless unless all elements of expense that will affect the results, are included. For instance, the cost of current delivered at the contact shoes should include not only costs of operation and maintenance, interest, depreciation, taxes and insurance on the power station, but likewise on the entire distributing system. If this is properly done, the real cost of current, as finally delivered at the electric equipment, will be found very largely to exceed the usual assumptions. The author's cost of current seems to me to be considerably too low.

On the other hand, the cost of maintenance and care of equipment should embrace not only wages and supplies, but also interest, taxes, insurance, maintenance and depreciation on the structures and real estate required to house and repair the equipment. Steam locomotives require extensive engine-houses, coal and water stations, ash-pits and appurtenances, often on very expensive lands, whereas electric equipment needs the simplest form of inspection sheds occupying limited areas of land. Also steam locomotives require extensive and complicated heavy-repair shops, usually at far distant points, that necessitate costly dead mileage and lengthy idle periods, while electric equipment because of its simplicity can be much more quickly repaired in nearby shops and returned to service. Many of these features have been mentioned by the author, but possibly their importance can be emphasized by giving some concrete examples from actual practice on the New York Central.

Because of less cost of maintenance of electrical equipment, and less idle time in shops, the greater cost of interest charges and depreciation is not only neutralized, but a net saving in repairs and fixed charges over steam equipment is effected of 19 per cent.

Electric locomotive inspection and light repairs, as compared with coaling, watering, drawing fires, repairs, etc., of steam locomotives show a saving in time in favor of the former of over 4 hours per day, equal to 18 per cent.

The electric locomotive, while busy, is a much more nimble and efficient machine than the steam locomotive, showing an increase in daily ton-mileage of 25 per cent.

While not so important in freight service, the question of locomotive weight is a large factor in a comparison of the relative economy of handling passenger traffic by steam and electricity. For instance, in switching service at the Grand Central terminal, 65 per cent. of the total steam ton-mileage is due to locomotive or "dead" weight, while the electric locomotive percentage is but 54 per cent., a saving for the latter of 11 per cent.

In the regular schedule service, the steam locomotive shows 51 per cent. dead ton-mileage as against 35 per cent. for the electric equipment, a saving for the latter of 16 per cent. When we realize that this saving of "dead" ton-mileage has a direct proportionate effect on the cost of fuel and current, and an indirect effect on wages and fixed charges, its importance is manifest.

The author calls attention to the speed advantage of electric over steam locomotives in mountain-grade operation. This is strikingly apparent in the New York Central installation, where the increase in coal consumption for car ton-mileage in high-speed service as compared with slow-speed service, is shown to be 165 per cent., whereas under exactly the same conditions the increased consumption of current for electrical equipment is but 18 per cent., a difference in favor of electrical operation of 147 per cent.

The net result of all of the economical advantages of electric operation, over steam, *for the conditions existing on the New York Central*, after including all elements of cost of additional plant, shows a saving in summer months of from 12 per cent. to 27 per cent., depending on the character of service. A larger saving may be expected under winter conditions.

In addition to this saving, the nuisances and dangers from smoke and gas in the Park Avenue tunnel have been eliminated, and the capacity of the Grand Central terminal has been increased about one-third. Later when the New Haven Company effects its change of power, complete electrical operation in the tunnel will permit the use of shorter blocks, and correspondingly increase the capacity of the four-track main-line entrance to the terminal.

I feel sure that the author will be pleased to know of this actual demonstration of the correctness of many of his views, and that the members of the Institute, regardless of their advocacy of rival systems of electrification, will take pride in the successful inauguration of this pioneer trunk-line installation, on such a large and complicated scale.

It might be well to add to the author's keynote *capacity*, the equally important one of *efficiency*, as the two combined, applied to the problem under consideration, will demonstrate whether or not the adoption of electricity is justifiable from the standpoint of economics.

Cary T. Hutchinson: I think that Mr. Armstrong gives the clearest statement of the capacity of steam and electric locomotives that I have seen. I agree with Mr. Armstrong that no project of electrification of trunk lines has up to the present been undertaken from an economical point of view. The matter has so far been determined by special considerations, such as the terminal problem in New York City, or the mountain-grade problem, or something similar. I doubt whether there are sufficient data on hand to permit the making of an accurate estimate of the total annual cost of electrical operation of any steam road; all data on the subject that I have seen are subject to criticism from one point of view or another.

Mr. Armstrong considers especially two points; the relative capacity of steam and electric locomotives as machines, and the relative cost of operating the two. I think, however, that he does not emphasize strongly enough one feature of the capacity of electric locomotives, that is the capacity in *continuous service*.

Regardless of the type of motive power, the design of a locomotive is limited to a certain weight on each driving axle, the maximum being about 50,000 pounds; the coefficient of adhesion, as Mr. Armstrong states, in steam locomotive practice is taken at about 22 per cent. Each driving axle will then be able to deliver a tractive effort of 11,000 pounds, and a draw-bar-pull of, say, 9,000 pounds. A steam locomotive can exert this draw-bar pull continuously, up to a certain speed determined by the capacity of its boiler, which for the sake of illustration may be taken at eight miles per hour, so that in freight service each driving axle will give a continuous duty of 9,000 pounds. Owing to the limitations of space, no electric locomotive can be built to deliver continuously a draw-bar pull of 9,000 pounds per driving axle; probably 5,000 pounds is the maximum that can be obtained; that is to say, an electric locomotive cannot work *continuously* at a coefficient of adhesion greater than about 12 per cent. Therefore, for continuous service at low speeds a steam locomotive, for the same weight on drivers, can pull from 60 to 100 per cent. greater load than an electric locomotive.

The electric locomotive can, however, deliver this draw-bar pull at any speed that it is practicable to use, the limitation being fixed by the equipment and the track, and not by the locomotive. The draw-bar pull of the steam locomotive falls off from the critical speed of, say, eight miles per hour, as is well brought out by Mr. Armstrong in the paper, whereas an electric locomotive, designed for the purpose, will give its continuous drawbar pull at any practicable speed; hence, at a certain higher speed the two locomotives will pull equal loads continuously, at say about 16 miles per hour. At all higher speeds the electric locomotive will have the advantage.

The size of an electric motor is determined principally by the torque that it must exert and not by the speed at which it must exert this torque; hence a locomotive designed for 10 miles per hour and a draw-bar pull of say 5,000 pounds per axle, can, by changes in the windings, which will not change the size or weight of the motors, exert a draw-bar pull of 5,000 pounds at 40 miles per hour, or any other practicable speed. This is the great advantage of electric as compared with steam locomotives.

Another way of looking at the matter is that electric locomotives are designed for the *average* work to be done, steam locomotives for the *maximum* work, since an electric locomotive designed for the average work will under all conditions easily be able to handle the maximum work. The use of the electric locomotive then makes it unnecessary to consider the ruling grade as a limiting feature to the capacity of the locomotive, whereas it must always be the limiting feature to the capacity of a steam locomotive. An illustration may make this clearer.

The six-axle Mallet compound locomotive used by one of the railways will pull, on the mountain division, having a grade of 2.2 per cent., an average of about 800 tons at a speed of 8.5 miles per hour, delivering therefore about 1,200 horse power at the driving wheel. The locomotive weighs 250 tons with tender; the output is equal to 4.8 horse power per ton total weight. An electric locomotive weighing 100 tons, all on the drivers, will haul the same load up the same grade at 15 miles per hour and will develop approximately 1,800 horse power, equal to 18 horse power per ton. In other words, the power developed per ton on drivers in the electric locomotive is four times as great as in the steam locomotive.

Moreover, an electric locomotive could easily be designed to exert the same draw-bar pull at a speed of 20 to 25 miles per hour, and have no greater weight, than for 15 miles per hour. This Mallet locomotive will pull a load of only 530 tons up the grade at a speed of 15 miles per hour, using Mr. Armstrong's curves as a basis. The comparison on a basis of 15 miles per hour is then:

MALLET.	
Engine and tender	250 tons
Train	330 tons
Total	580 tons
ELECTRIC	
Engine	100 tons
Train	800 tons
Total	900 tons

or the useful load at this speed is 2.4 times as great. This is merely another way of saying that steam service is incapable of handling heavy loads at high speeds.

The great advantage of the electric locomotive is, therefore, in the much higher speed possible. There is no inherent reason why a freight train should run at a lower speed than a passenger train; they do run at lower speeds simply because locomotives can not be built to haul them at the higher speeds, but the electric locomotive will probably change this and the speed of the freight service will be increased very greatly.

Another point should be noted in the above comparison. The steam locomotive weighs 150 tons more than the electric locomotive; assuming a duty of 100 miles per day, there are 15,000 ton-miles daily dead haul, which at the rate of 2 mills per ton mile amounts to about $30 per day, or say $10,000 per year. This is a clear saving in favor of electric locomotives. It can also be viewed as permitting an increase of 150 tons in the possible train load, and from this point of view the net earnings of an electric locomotive would be greater than that of a steam locomotive by the 150 tons extra load.

Something has been said by Mr. Armstrong about three-phase locomotives. I have recently decided to use the three-phase locomotives for the Cascade Mountain grade of the Great

Northern Railway, and among the reasons leading to this decision was the fact that the locomotive would have a fixed speed and could not be operated at a greater speed on the down grade. This equipment is for the freight service of the road only, at a place where much trouble has been caused by trains running away on the down grades.

Another reason leading to this decision was the recuperation on the down grade; this is valuable, not so much in the saving of energy, for in this case the additional energy, being supplied from a water power plant, would cost nothing, as in lessening considerably the capacity of power house required for any particular service. Two tons going down the grade will pull one ton up the grade; it is therefore necessary only to supply power for the tonnage up grade in excess of the down grade tonnage; with a system of train dispatching having this in view, a material saving can be made.

W. S. Murray: Law or economy brings electrification of railroads. It is peculiarly interesting, too, to note how economy hugs up to law, if law has been the cause. After law has had its turn, then comes the turn of the engineer. Such conditions may be levied by the law as to make impossible the operation of a certain piece of railroad mileage as economically by electricity as by steam. It is the duty of the electrical engineer to choose such a system consistent with safety and the guarantee of continuity of service, which will increase to a minimum amount the original operating expense. When economy dictates the electrification, again it is the duty of the electrical engineer to elect a system consistent with safety and continuity of service, which will decrease to a maximum extent the original operating expense.

The closing sentence of Mr. Armstrong's paper is:

> The keynote of electrification is capacity; by approaching the problem from this standpoint only can full benefits be obtained.

I am in full agreement with Mr. Armstrong on this score, except I feel that while he has furnished the horse, there has been no mention of the carriage and what the carriage contains; in short, I should have said the keynote of electrification is "ton-miles", then capacity to handle it. The track capacity of a railroad is tremendously enhanced by electrification, but ton-miles must be on hand to make necessary the increased locomotive capacity.

I cannot escape a decided exception to Mr. Armstrong's reference, "Petty economies effected in coal consumption and cost of locomotive repairs". Examining the principal heads under operating expense, we find "maintenance of way and structures", "maintenance of equipment", "conducting transportation" and "general expenses". There is little choice in this list that electrification can detach upon which to practise its economies other than fuel and locomotive repairs. Of course the inference concerning the general increase of track capacity and operating facility, together with the fact that electrified lines offer more inducement for traffic in general, is not lost, but I cannot withhold figures that have come within my personal observation and keeping, which have a value keenly *important* rather than "petty" and, indeed, point directly to and are a demonstration of the keynote to electrification; namely, ton-miles.

In a previous contribution to the Institute's TRANSACTIONS in connection with the Stillwell-Putnam paper on the substitution of the electric motor for the steam locomotive, I presented figures that were worked out in a faithful effort by all concerned in it to secure what could be absolutely relied upon as the resistance of the main line of the New York, New Haven & Hartford Railroad Company between New Haven and Woodlawn. I shall briefly say in regard to this work, that after days of careful indication of steam locomotives on east- and west-bound runs with trains of varying weight for express and local-express service, the resistance for these several conditions was obtained, and the real relations between the ton-mile, the pounds of coal per ton-mile, and the horse-power-hours per ton-mile, were established in figures, upon which has been based the power house capacity necessary to operate the electric trains of the New Haven road. This effort was made to secure the actual service conditions rather than to depend on hypothetical resistance curves, the opinions on which are conspicuous for their wideness of variation.

Generating, transmission line, and railway equipment efficiencies are too well known not to be able, having determined the rim horse power required for propelling trains, to figure back to the power house the amount of the kilowatt capacity required to operate a predetermined schedule of trains. We cannot afford to quarrel with the machine efficiency of the steam locomotive. It is the equal of the machine efficiency of the electric motor morning, noon, and night. We shall take issue, however, on the efficiency which lies behind the two engines, viz: the generation of steam in the boiler of the locomotive versus its generation at the power station with its attendant transmission and conversion into electricity for application to the motors driving the locomotive.

The following table shows the saving of fuel which will be effected on the New York division when all freight and passenger trains, now operated by steam, receive their draw-bar pull by the electric method of traction.

	Ton-miles per annum	Tons of coal steam traction	Tons of coal electric traction	Cost of coal steam traction	Cost of coal electric traction	Saving of electric over steam traction
Express..............	592,240,000	57,447	29,870	$183,830	$89,620	$94,210
Local-express........	348,000,000	58,300	28,600	186,560	85,800	100,760
Freight..............	2,223,000,000	187,844	139,010	563,530	417,030	146,500
	3,163,240,000					$341,470

In connection with the work done in the field to secure the data as compiled in the table just read, a diagrammatic tabulation of the observations considered pertinent to the test was made,

Showing
Average cut-off variation
Boiler pressure variation
Water consumption
Indicated horse power
Grade profile.

Ten locomotives were included in this test, and eighteen days of consecutive observation of performance were utilized.

Briefly, this diagram indicates that in express work 2055 indicated horse-power-hours are developed in the evaporation of 57,594 pounds of water, giving an average, therefore, of 28 pounds of water per indicated horse-power-hour; and on local trains this figure is slightly increased, the evaporation being 42,987 pounds of water for 1435 horse-power-hours, making the rate, 30 pounds of water per indicated horse-power-hour. I mention these figures, as we are all familiar with the turbine guarantees of 20 pounds of water, including auxiliaries, per kilowatt-hour at the switchboard which, reduced to a horse power basis, would be 15 pounds of water as measured at the switchboard. Remembering the ratio of 7 to 10 in the evaporation of locomotive vs. stationary boilers per pound of coal, it is not a stretch of conscience to concede that twice the draw-bar pull can be developed by the electric method of traction for coal burned under the boilers of stationary plants vs. coal burned in the fire-boxes of locomotives.

In that contribution, I also submitted figures bearing on the cost of repairs and maintenance of 20 steam, freight, and passenger locomotives; these have been kept most carefully over a period of one year and show 8.1 cents per locomotive-mile for freight engines and 5.6 cents per locomotive-mile for passenger engines. The engine mileage of the New York division of the New Haven road amounts to about 4,836,992 miles. This mileage is divided for passenger and freight service into 2,993,328 and 1,843,664 miles, respectively. These figures were based on week ending October 25, 1907, and it is to be noted that it will, therefore, be below the average, on account of the summer months bringing the heaviest traffic. This means an operating cost of $316,962.00 per annum, for the maintenance and repairing of engines.

The average figures that I have been able to secure on electric engine repairs per locomotive-mile are about 2 cents. Increasing this figure 25 per cent. for safety and assuming the same number of electric engines replacing steam locomotives, (as a matter of fact there would be less electric engines required on account of the greater mileage per diem derived from electric locomotives) the total would be $120,924.00 per annum, showing a saving over steam locomotives of $196,038.00. Therefore, the net saving on fuel and locomotive repairs in favor of electrification gives a round sum of $562,470.00 per annum. This, upon a capital basis with money at 5 per cent represents $11,249,400.00, a rather effective credit on the expense necessary to invest.

Messrs. Stillwell and Putnam's exhaustive and comprehensive analysis of the statistics of railroads for 1904, compiled by the Interstate Commerce Commission, and proof sheets of the report of the Commission for the year 1905, give the undeniable records of railroads of this country; and the averages for over five years, as shown in the paper read by them before this Institute, show fairly and honestly, where and where not economies may be effected. Of the four principal headings of operating expense as mentioned before, two of them, viz.: "maintenance of way and structures" and "general expenses" may be equated. Of the remaining two, viz.: the "maintenance of equipment" and the "conducting of transportation," the first of these indicates that operation could be effected by electricity at an expense of about 63 per cent. of that of steam; and of the 37 per cent. saved, 75 per cent. of this is on account of the economies in the repairs of electric vs. steam locomotives. Our steam experience, to date, enables me to confirm these figures of Messrs. Stillwell and Putnam.

Concerning the second item, viz: the conducting of transportation, which is generally the largest item in the operating expense of any railroad, it is to be noted that the estimated cost of operation by electricity is 79 per cent. of that of steam; and it is safe to consider that of the 21 per cent. saved, 90 per cent. of this is on account of fuel and round-house expenses. These figures are confirmed by the practical investigation which I have been conducting in an effort to secure the relative operating costs of the New York Division by electricity vs. steam.

Mr. Armstrong's paper is full of a most interesting line of initiative, and is particularly attractive to me on account of the broad scope in which he has handled this subject. The matter of fuel and locomotive repairs, has been one of such interest to me that I must ask the indulgence of the Institute in having dwelt with such length on these two details, from a paper which has covered so much other ground.

I may say that I almost regret to see the disappearance of the steam locomotive from the electric zone of the New York, New Haven & Hartford Railroad, as contrasts in operation are never better seen than when they are almost inseparately attached to each other.

In closing, I would refer to two details in operation, which unquestionably increase the capacity of a given trackage for trains operated by electricity, viz: yard switching, and turning of engines at terminals. I believe it is safe to say that our experience, to date, has demonstrated that in the first instance double the amount can be accomplished in the same time; and in the latter, electric engines are ready to make their reverse train movement in 25 per cent. of the time required by steam locomotives, assuming that the water-tanks, ash-dumps and turntables, are within the yard limits of the terminal.

Wm. McClellan: We shall not be able to state positively what basis there is for electrification on the score of reduction in operating charges until we have a complete engine stage equipped electrically, with no steam locomotive shops, no steam repairs, no unnecessary buildings, but everything equipped to handle electrical equipment only, in the most economical manner. For this reason I think that the speaker of the evening has taken the proper view, when he bases his whole argument on capacity. He believes that heavy grades will prove the most fruitful field in which to start, and we must agree with him very heartily. It cannot be gainsaid that he has proved his case so far as this point is concerned in this paper. It should not be forgotten that all electrification to date has included a very great change in operating conditions and frequency of train service. As a result, electrification has been charged with many expenses which properly belong to amplification of the service and not to electrification proper. To get a just comparison in such cases it would be better to estimate what it would cost to give the increased service, both in quantity and quality, by steam locomotives, and compare this with the estimate required to do the same work by electric locomotives. In most cases I believe it would present the case for electrification in a much more favorable light than the way it is usually done.

I must also agree with the author that the electrification problem is not a substitution problem. It involves taking the traffic problem of the railroad and solving it along wholly different lines, from wholly different points of view. An electric locomotive is not something that is designed to replace a steam locomotive taken off rails. It has different capabilities, different possibilities, and these must be considered as influencing the whole traffic problem. The very greatest stress should be laid on this point in discussing the matter with our steam locomotive friends.

C. L. de Muralt: My belief is that, when one or two of the large railroads have been electrified, we shall find economies in operation to have slipped in, with or without intention. But the largest electrification work in the near future will likely be done for the reason that very much more traffic can be handled over existing tracks with electric locomotives than with steam locomotives. My office has recently had occasion to work out a problem where a road with something like eighty miles of double track was actually nearing the end of its ability to handle traffic with steam locomotives. The question came up of adding new tracks to increase its capacity. In this case, there would have been two additional tracks which would have cost something like $15,000,000. On the other hand, a complete electric equipment for the old tracks, comprising power stations, distributing system, and locomotives, will cost only about $3,000,000. The handling of the present amount of traffic by electricity will save in operating expenses something like $200,000 out of $800,000 and with the electric equipment pushed a little harder, there will be a chance to increase traffic forty to fifty per cent. over what the tracks will stand under steam. Here, therefore, is a case where electricity should be used and electric equipment installed just as soon as the $3,000,000 can be raised.

Mr. Armstrong has not only reaffirmed that increase in capacity is the keynote, he has also shown us what he understands by capacity and what we should all understand by that term. It is a pity that so many engineers, who have to draw comparisons between electric and steam locomotives, are not quite clear on this point, and that comparisons have been made which are really quite a little misleading. It is not so much the tractive effort or the draw-bar pull which a locomotive can give, but the speed at which that draw-bar pull can be developed, which is important. And that is what Mr. Armstrong so nicely points out, when he defines as capacity, not merely draw-bar pull, but the product of draw-bar pull times speed. From this viewpoint Dr. Hutchinson's statement will look different. If I understand him correctly, he believes that steam locomotives could give about 9000 lb. draw-bar pull per axle, while no electric locomotive could be built to do the same. Personally, I am absolutely convinced that electric locomotives can do better than that. But, even if an electric locomotive could give only 4000 or 5000 lb. draw-bar pull per axle, but can carry that 4000 or 5000 lb. up to three or four times the speed at which the steam locomotive can develop 9000 lb. draw-bar pull, cannot the electric locomotive handle more traffic? In other words, is not its actual capacity much larger than that of the steam locomotive? As an illustration I have in mind a high-speed steam locomotive of the New York Central Atlantic type, which weighs about 160 tons, and develops a tractive effort at 45 miles per hour of about 13,000 lb., while the New York Central continuous-current locomotive weighs about 95 tons, and will carry at the same speed of 45 miles an hour a tractive effort of about 14,000 lb. In the one case about 80 lb. per ton, and in the other about 150. A European type of three-phase electric locomotive weighs about 70 tons and will carry at 45 miles an hour about 23,000 lb. of tractive effort, which is a still better showing. In short, I believe the question raised by Mr. Armstrong, and the solution offered by him, both show clearly what we are likely to come to: those lines will probably first be electrified which, with steam as motive power, are now at the limit of their traffic capacity. Electricity will show that for a comparatively small expenditure of money we can increase the traffic of such lines considerably, and I think we may look to an early use of electric locomotives for such purposes. That type of electric locomotive will in the end prove to be the most useful, which in a given unit weight is able to concentrate the greatest amount of tractive power.

W. N. Smith: There is very little to add to what may be called the statistical feature of Mr. Armstrong's paper. He has had exceptional opportunity to go into such parts of the relative costs as are covered by the scope of his paper. But the problem is so complicated that the part of it which has here been covered in some detail does not cover the whole question. I agree fully with those who have remarked that the items which he has called petty or incidental are of considerable importance. They depend, of course, on the conditions of the particular road which the engineer may be called upon to investigate. A mountain road, or a road with a continuous long pull of 20 or 30 miles up-grade, is a different condition from a broken profile, or a level profile, such as the road from which Mr. Murray has given some figures. It is a very interesting proposition to consider the total resistance to be overcome in drawing a train over a line, and it is a relatively easy matter to consider it from that standpoint when the road is almost absolutely level; but when a large amount of drifting comes into play, with long down-grades, or with a broken profile, the problem becomes somewhat more complicated. It is very true that the whole question focuses upon capacity; but there are several different ways of looking at capacity, and one of the aspects that has not to my knowledge been given very much consideration in most of the communications on the subject, is the *capacity for train movement* of any given piece of single-track railroad. This is really a deep question. It is one that railroad operating men are daily in contact with, and it is to them that any question of capacity must appeal first. They are the men whom, first of all, you have to convince that you can increase the capacity of a piece of track, and while the possibilities of double track, as to increase, are considerable, the possibilities of single track are considerably less, particularly if the profile is undulating and operating conditions generally are difficult. It is quite conceivable that it would be found impracticable to get as many trains over a given piece of single track as would be required to make it a financial object to electrify that particular section. In such a case, of course, electrification would be reduced to an absurdity.

I mention this simply as a possibility. I have not had opportunity to examine a particular instance of this type carefully enough to define where it would begin to be an absurdity, but I know that such a consideration is apt to be present, and cannot be left out of the calculation. The operating man's standpoint is of the greatest importance, and it is one, I fear, to which many electrical engineers have not hitherto given sufficient consideration. The general trunk line electrification work of the future, however, must be considered from that standpoint.

I suppose that considerably more than 75 per cent. of the mileage of the railroads of the United States is single track, and the cost of increasing the capacity of these roads by double tracking them, in order to enable a much greater number of trains to be run over the road in both directions, would stagger the imagination if it were estimated. Electrification is in some respects a simpler proposition to estimate on, in so far as cost is concerned, but there is no use trying to figure out how to run more trains over a piece of road than the road will accommodate. The questions of block signaling, turn-outs, and train-dispatching must enter into the problem first of all.

The capacity of the steam locomotive has been mentioned as being in some instances greater than could possibly be obtained continuously from an electric locomotive, but it occurs to me that this will depend to some extent on the conditions under which the steam locomotive is to operate. We know that up-grades of 30 miles or longer actually exist where a steam locomotive working at full power has to stop for water on the way up; of course it can go right along again at its maximum capacity after it has filled its tender, but when it has worked up to the point where all its water is exhausted, the locomotive must stop to have the supply replenished; and to that extent there must be some qualification to statements regarding the uniformly high capacity of a steam locomotive.

The question of load-factor has not been touched upon in the discussion of the cost of power. I will not undertake to discuss it, except to state that it seems to me rather an important matter to consider in making an estimate of what the cost of power will be in predicting the economic performance of an electrified section. Of course it goes without saying if the section is congested the load-factor will be high, but if the trains are few it will not be high and the cost per kilowatt will run up.

The weight of the tender has been mentioned, and any one who will examine the general data of the heaviest steam locomotives now being turned out will perhaps be somewhat surprised at the enormous weight of the tender, a dead weight, which, though a part of the motive power, cannot produce any tractive effort.

It is probable that a comparison with the consolidation type of steam locomotive will show a greater economy for electric power than will a comparison with the Mallet type of locomotive, which is said to be very successful in mountain work.

The various items of cost, even those called "petty", which enter into locomotive operation and maintenance, whether steam or electrical, are so variable that differences of a comparatively small number of cents per locomotive mile in a few items may make a large difference in the showing that the final tabulation will produce, and may throw the balance one way or the other, and every possible item of expense must be taken into consideration in making a comparison that will pass as valid when presented to the practical railroad operating man.

Chas. P. Steinmetz: The leading conclusion of Mr. Armstrong's paper seems to be that the advantage resulting from electrification is to be found in the increased capacity; that is, the ability of the road with the same trackage to handle a greater amount of traffic. This, however, means that the change from steam power to electric power is not a mere substitution of the electric locomotive for the steam locomotive, but a readjustment of the ways of operation; that is, an increase of the speed of operation of freight service by taking advantage of the feature of the electric locomotive to be able to carry its draw-bar pull up to a higher speed. We usually find, when introducing a more advanced way of doing a thing, that we have not a mere substitution, but to get the greatest benefit from the change, the method of operation must be rearranged. Nearly a century ago when the stage coach was replaced by the steam engine, the first attempts to attach the steam engine to the stage coach and pull it over the country roads came to naught, and steam propulsion became successful only by putting the locomotive on the railway track. A characteristic of the steam locomotive is that it is essentially a constant power motor. It gives approximately the same power whether running at high or low speed. The draw-bar pull, therefore, does not tell the whole story, but the limit is the steaming capacity of the boiler, and the faster you move the oftener you fill the cylinders, and since you cannot for a long time exceed the ability of the boiler to produce steam, you have to cut off earlier, and so get less draw-bar pull. Not so in the electric motor; in this the limitation essentially consists in the constant loss of power. The limit of the electric locomotive is that it must lose only so much power in the motor, in the general average, as to be within safe heating limits. Since efficiency rapidly increases with the speed, it means you can get more power out of it at higher speeds, up to a certain limit, and therefore the electric locomotive is best at higher speeds than the steam locomotive, and we have to take advantage of this feature if we desire to show the best results. It, therefore, as you see, does not mean a mere substitution, but also means a readjustment especially of the most important part of the railway service, the freight traffic, for higher speed. Higher speeds necessarily mean increased capacity of the system, even without any increased draw-bar pull, even with less draw-bar pull, and in this feature I believe lies the main advantage of electric traction; but it makes it necessary to readjust the method of operation to the changed condition of railroad motive power, to get the best results of the electric locomotive. You may merely substitute, but you get better results by not merely substituting, but also by increasing the speed to operate at the most economical speed of the electric locomotive, and this in general is higher than the most economical speed of the steam locomotive.

A. H. Armstrong: In working up the comparison of the performance of the steam and electric locomotive I was impressed with the fact that the greatest benefit to be secured seemed to lie in the electrification of mountain-grade divisions. That is, the greatest necessity for electrification as well as the greatest return for the money invested are met with on heavy grades, and I am, therefore, very much pleased to find that the economy figures given by Mr. Wilgus as obtained in actual service on the New York Central check up in some degree the final results I have arrived at by calculation. Also that the calculated figures by Mr. Murray for another section of a level road, New York, New Haven & Hartford Railroad, indicate a comfortable return upon the capital required for electrifying the New York division of that road. With these figures for level operation it would seem as if my general conclusions for the electric operation of mountain-grade divisions were very conservatively arrived at.

In regard to the remarks of Dr. Hutchinson, that a total draw-bar pull or tractive effort of 9000 pounds could not be continuously sustained by an electric locomotive, I have only to point out two or three facts of operation which may perhaps have been overlooked by him in making the statement. With 50,000 pounds per axle and a tractive effort of 20 per cent., which is conservative for average conditons of track, 10,000 pounds of tractive effort is available. In practice, however, it is not possible to work any locomotive at this tractive effort continuously irrespective of its type of motive power, owing to the broken character of all profiles, as even on mountain-grade sections crossing a continental divide the grades are not uniform, but the average grade is seldom more than 60 per cent. of the maximum or ruling grade. For example, the greatest extent of continuous grade in this country is on the Sacramento Division of the Southern Pacific system, which has a 1.54 per cent. average grade for 83 miles with a ruling grade of 2.2 per cent. In other words, during the rise of 7000 feet in 83 miles the average grade is 70 per cent. of the ruling grade. A locomotive operating over this division will be called upon to sustain, say, 60 per cent. of its maximum tractive effort, thus leaving a margin of 10 per cent. over the demands of the ruling grade in order to start up the train on maximum load and grade conditions. Under these conditions the electric locomotive would not in any way suffer in comparison with the steam locomotive, as the heating of the motive power would not in any way prohibit the delivery of 6000 pounds per axle at any speed that may be safe in operation. Furthermore, it is necessary to take into account the very serious delays occurring on single-track roads where the traffic may be heavy; so that all operating conditions considered, I see no reason why it should not be possible to keep the temperature rise of the electric motive power well within safe limits in practice.

In choosing the word "petty" I seem to have been particularly fortunate in irritating Mr. Murray into giving some very valuable data pertaining to tests made by him on the

New York, New Haven & Hartford tracks with steam locomotives. Mr. Murray's figures are going to prove very interesting reading when we have a chance to go into them in detail at greater leisure, but I am surprised to see that such a low steam consumption (28 to 30 pounds per i.h.p. hour) was arrived at in actual tests. This steam consumption could be looked for by indicator, but it seems rather low if it includes all the stand-by losses of the locomotive not in actual operation.

In dealing with steam locomotive statistics I have found it necessary to divide the determination of coal and water consumption into two parts. First, that required for the actual hauling of the train; secondly, that lost while coasting or standing still. For instance, I show in the paper that on a certain road there are some 400 pounds of coal and 4000 pounds of steam used per hour while locomotives are idle at terminals, turn-outs, or coasting down grades, while the performance of this simple consolidation engine when actually hauling a train corresponded to a steam consumption of 28 to 30 pounds per boiler horse-power-hour with an evaporation of approximately six pounds of water per pound of coal. The Mallet Compound requires more coal than this chargeable to stand-by losses, and further requires the admission of steam in order to coast down grade at a speed much higher than 10 or 12 miles an hour. All of these losses in steam locomotive operation amount up to a grand total that in many cases will show a considerable excess cost over the cost of electric power for hauling the same tonnage with electric locomotives. Hence my feeling that the figures submitted by Mr. Murray are somewhat low for the total coal and water consumption of the locomotive for twenty-four hours in regular service.

I must adhere to my position taken in the paper that economy of operation as regards coal consumption does not constitute any sufficient cause for electrification in the great majority of cases, and I think we cannot bring out this fact too strongly. It is not sufficient to show the management of steam roads that they can get a return of 10 per cent. or even 20 per cent. upon $10,000,000 or more required for electrification, as they are not looking for investments of this character. Careful consideration, however, will be given to any report showing means of increasing gross receipts or that will offer a reliable substitute for the double tracking that may be necessary to provide for a rapidly increasing tonnage. I must adhere, therefore, to the idea that the main reason for electrification of roads other than terminals, tunnels, etc., is embodied in the increased capacity of the electric locomotive, providing increased tonnage capacity of the tracks, decreased running time, etc.—all of which guarantee an increase in gross receipts and a possible saving in expenditure for additional tracks, reducing ruling grade, etc. That this electrification will be accompanied with a gratifying reduction in operating expenses is a still further argument for replacing the steam locomotive, but it is not of sufficient importance in itself in the majority of cases, to encourage electrification.

I note the doubt expressed by Mr. Smith as to the saving effected in the electrification of single track roads, and would state that it is on just such roads as these where the greatest saving can be effected both in cost of electrification and in operating expense. A large volume of traffic is carried over a single-track road under the greatest difficulty and at considerable expense. This applies especially to trains hauled by steam locomotives which are capable of only six or seven miles per hour schedule speed up severe grades, and add considerably to the number of signal stops by reason of their limited radius of action with their coal and water supply. For instance, a steam locomotive working at an average of 75 per cent. of its full boiler capacity on a mountain grade cannot cover more than 15 to 20 miles without taking on more water, in this respect very much resembling the electric automobile forced to return frequently to its charging station for the material for a fresh start. It is entirely safe to say, therefore, that the total tonnage capacity of a single track will be very much increased with the adoption of the electric locomotive, and the cost of such electrification in some cases may be considerably less than the capital required to double track or duplicate the single track already installed. In other words, where a mountain-grade division has reached the maximum tonnage capacity possible with single track, and it becomes a question of double tracking with steam locomotives, a careful analysis of the conditions may show that electrification of the present single track may be accomplished with a lesser expenditure and be followed with a greater return upon the money invested.

I agree with Dr. Steinmetz in the views expressed by him and would draw the attention of the members to the entire revolution in methods of handling short-haul passenger traffic by the introduction of the electric motor. I believe also that the introduction of the electric locomotive will bring about fundamental changes in the method of handling freight traffic by reason of the many inherent advantages enjoyed by the electric locomotive and not shared by its steam competitor.

W. S. Murray (by letter): In answer to Mr. Armstrong's question as to whether the coal measurement was made for the full 24-hour day, including the hours during which the engine was not doing revenue work, such as time spent in the round-house, over ash-pits, cleaning fires, etc., I would say that this was the case; the idea not being simply to get the rate of coal per horse-power-hour while the engine was making its revenue runs, but to secure the real commercial rate or day consumption, which governs the bill the railroad company pays.

A paper presented at a meeting of the Ithaca Section of the American Institute of Electrical Engineers, Ithaca, N. Y., Dec. 6, 1907.

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PRACTICAL ASPECTS OF STEAM RAILROAD ELECTRIFICATION

BY W. N. SMITH

In view of the extended treatment which has already been accorded to this subject on the floor of the Institute, and elsewhere by distinguished engineers during recent years, it is difficult and in fact hardly necessary to add anything to the electrotechnical side of the subject. So many are the electrical schemes proposed for the accomplishment of the various ends that it now seems desirable to examine the subject from standpoints other than electrical, in order to facilitate intelligent consideration of the problem as a whole.

The trend of some of the papers that have recently been presented, and the discussions that have accompanied them, convey the impression that electric railway engineers are ready to apply any one of several well developed systems of electrical propulsion to any railroad, and attempt to make it pay. Although much has been published, most of it is of so general a nature that it is only partly convincing; and while it doubtless stirs up professional enthusiasm and tends to keep up active emulation in devising attractive schemes and systems, the railroad man with a particular problem to solve is almost as much in the dark as ever as to the practical value of the new motive power for his particular conditions.

Although at first sight there would seem to be as many different types of problem as there are railroads to be electrified, the writer believes that some general classification is possible; and while it might be further specialized by paying especial attention to topographical and transportation features, which may be distinctly peculiar to each individual case, the writer thinks that railroads in general could be classified as follows:

1. Suburban lines or sections.
2. Tunnel and terminal sections.
3. Heavy trunk lines with low grades, dense traffic, and more than two tracks.
4. Double-track trunk lines with grades under one per cent.
5. Single-track trunk lines with grades under one per cent.
6. Mountain railroads with single or double track, with long grades steeper than one per cent.
7. Single-track branch lines or feeders.

It would seem that a large proportion of the railroad mileage of the country could be included in some one of the above classes, and there are individual railroad companies which have mileage under all of them.

The question of density of traffic is often brought up in discussions of steam railroad electrification, and it is generally admitted that the problem deals with the economic effect of increasing the train movement; but the physical features involved in the study of train movement are so difficult to define in general terms, and the number of concrete cases is so infinitely great, that very little information has been gathered or classified that will enable general rules to be made for determining where, so far as train movements are concerned, it becomes economical to abandon steam in favor of electric motive power. It seems to the writer that this very complicated subject must be approached by degrees, and upon the basis of concrete illustration drawn from examples of conditions as classified under the above suggested headings. Such a treatment of the problem in general would make it more attractive to those charged with the practical management of railroads—the men to whom general curve sheets, which appeal to theoretical electrical considerations, are apt to be meaningless unless accompanied by voluminous explanation. As generalities, solutions by curve sheets are usually of very limited application.

The fact has recently been emphasized that hitherto steam railroad electrification has been carried out only in very special problems, coming mostly under the headings: (1) Suburban, (2) Terminal, and (3) Heavy trunk lines, in the above classification, but only for relatively short sections. Considerable attention is now being given to problems of the class under (6) Mountain-grade division, and one such project is actually under way in this country.

The electrification of a portion of the Erie Railroad Company's Rochester Division, could properly be classed as that of a feeder or branch line under (7), but even that, as at present constituted, is only a partial electrification, as only passenger traffic of the suburban or interurban type is handled electrically at the present time, steam power still being used for through passenger and for all freight service. The West Jersey and Sea Shore electrification should also be put in this class, though an enormous summer excursion business is its principal justification.

Furthermore, the writer believes that in discussing a problem of such tremendous proportions, the matter of the particular electric system to be employed should not necessarily be placed foremost, but that practical railroad operating conditions must be regarded as of paramount importance. It is, of course, impossible to cover the whole field in a paper as short as this is intended to be, but it is certainly in order to get a larger perspective upon the activities of the railroad as a whole, rather than to keep our attention focused upon the purely electrical part of it.

The fields of activity concerned in the electrification of a steam road may be subdivided into two broad divisions.

1. The electrification project, as it calls for the services of the manufacturer and the engineer.

2. Railroad operation, which in this connection may be considered as threefold:

a. Financial or economic,

b. Railroad construction or standardization, and

c. Transportation or operative.

Reviewing these divisions, the electric railway industry occupies a peculiar position as compared with the general trade in railway appliances.

A practical monopoly of electric propulsion apparatus is divided among a very few large companies. This is somewhat similar to the general situation as regards steel rails, and steam locomotives, both of which commodities are produced by a relatively small number of manufacturers. Until recently the steel-rail situation was kept very close to a uniform standard in quality of product, as well as in price, but there having been a strong protest by the railroads against the defects that have been developed in quality, this feature is now undergoing revision by the steel companies. With respect to locomotives, however, more liberty of action is preserved by the railroad companies The requirements of the motive-power departments of different railroads are so diverse as to afford little opportunity for wholesale standardization, which is a matter that is left entirely in the hands of the railroad customers rather than with the manufacturers. There are certain tendencies toward standardization on a large scale, such as that made possible by the associated Southern Pacific, Union Pacific, and allied lines east and west of the Mississippi, for the sake of securing economy in maintenance and operation; but such attempts as have been made toward standardization on the part of the locomotive manufacturers seem to have pertained more to certain interchangeable parts of the locomotives, than to types which have usually been developed by the needs of individual roads. With electrical motive power apparatus, however, the art is relatively much newer, and the number of trained specialists is fewer, and mostly concentrated at the manufacturers' shops so that the opportunity afforded the manufacturers to inspire and direct the formation of their customers' ideas on electric propulsion has not been neglected. It has had a great effect upon the development of the industry.

This does not mean that the manufacturing engineers' judgment may not be excellent concerning questions pertaining solely to the design of the apparatus intended to meet particular conditions. It can hardly be expected, however, that manufacturing engineers can always look upon their apparatus in any other light than that of a special commercial product, the responsibility for whose performance comes home to themselves in particular, they are therefore prone to consider the various conditions of construction and operation from the standpoint of the effect of railroad conditions upon their apparatus as more important than the sum total of effects of the apparatus upon the railroad problem as a whole.

In general, standardization of any railroad equipment on the part of manufacturers is more usual in commodities which the railroad companies cannot or do not ordinarily manufacture themselves in their own shops. Railroad companies have been compelled to leave to steel mills the work of making the rails, but they have frequently made a practice of building locomotives in their own shops. Their necessary repair-shop facilities place them in a position to furnish for their own locomotives and cars whatever equipment a locomotive manufacturer or car builder may decline to furnish. It is quite possible that some years hence railroads will devise their own systems, and build their own electric motors and locomotives. There is even now a tendency in this direction by the large trolley railway companies who make many of their own electrical repair parts. The Standardization Committee of the American Street and Interurban Railway Association has made an excellent beginning along the same general lines as have been followed in years past by the Master Mechanics' and Master Car Builders' Associations of the steam railroads; and in the course of time it will undoubtedly come to pass that advances in standardization will emanate not so much from manufacturers' engineers as from the railroad companies' own electrical engineers, who will be held directly responsible for the results.

By the time that twenty or thirty roads have electrified their lines, wholly or in part, the attitude of their operating and maintenance engineering forces may become an important factor in the situation; and the commercial rivalry now shown in devising and perpetuating electric systems will then be diverted from its present tendencies, toward the more natural function of competing to furnish apparatus as specified by the railroads.

The consulting engineer's standpoint at the present time is that of an interpreter between the manufacturer and the railroad. He has to translate the limitations of the electrical apparatus in terms easily understood by railroad officials, who generally do not pretend to be electrical experts; and he must be sufficiently familiar with railroad standards and practice to insist that the electrical manufacturer shows due regard for the general fitness of his apparatus to railroad purposes, both in design and reliability. He is frequently charged with a very grave responsibility in aiding the railroads to decide some very fundamental and perplexing question arising from the relationship between the old art and the new. Although he may write new and complete specifications for all the parts of manufactured apparatus involved, he is generally not called upon to design it in detail, as that function is still practically monopolized by the manufacturing companies, though subject in some degree to the consulting engineer's control. He has not only to act as mediator between the railroads and the manufacturing companies, but he must also secure coöperation between the various departments of the railroad itself which are intimately concerned with the work he is doing; that is to say, the construction, maintenance, mechanical, and transportation departments—all of which, in many instances, have to be consulted with reference to a single detail. The pioneer engineering work of steam railroad electrification up to the present time, has largely been done on the initiative and with the aid of consulting engineers, whose usefulness to the railroad in the above described capacities has been very notably demonstrated.

The standpoint of the railroad management as above suggested comes under three general heads; the financial or economic, the constructive and maintenance, and transportation.

The control of a railroad being in the hands of those who represent the investors, the financial aspect of any improvement is the first to receive consideration. The financier looks upon the problem of railroad motive power as only one of a large number to be solved from the standpoint of the maximum possible return for every dollar invested, whether it be for the purpose of reducing the cost of conducting the existing business, or of largely increasing that business. A project for the electrification of a railroad is usually attractive, because of the increased amount of traffic it becomes possible to handle in proportion to the expense of handling it. This is usually directly accomplished by increasing the speed of revenue train-movement over a given piece of track, and by reducing the amount of non-revenue train-movement.

Such questions are, of course, most pressing where conditions of traffic congestion are most severe; and for that reason most of the heavy railroad electrification has hitherto been worked out in and near New York City, where the maximum movement of passenger trains is required in the minimum amount of area available for terminal facilities. The electrification, first of the Baltimore & Ohio tunnel, then the Long Island Railroad, the New York Central Railroad, the New Haven Railroad, and the Pennsylvania Railroad's New York terminal now under construction, was called into being, first of all by public necessity, and secondly by the desire of each railroad company to place itself in a position where it could handle at its terminal the maximum traffic that its lines and territory could develop, steam motive power having for one reason or another reached its limit. These installations are distinctly special in character and can hardly be taken as representative of the general railroad electrification problem, although the general principle of increasing net earnings by increasing capacity is of universal application. In much of the work referred to about New York City, the prospect of immediate returns upon the investment had to be considered as of secondary importance. But in proportion to the total mileage of the country which may ultimately prove fit for electrification, territory of such a character is relatively small in extent. Tunnels and terminals like those mentioned have been electrified simply because of the physical impossibility of meeting the business and public necessities in any other way.

The more general cases, however, are not likely to be regarded by the financier in quite the same light, although it is believed that they can be more convincingly solved on their financial merits alone than is possible in the case of expensive metropolitan terminals. Each case that is brought up for solution must, through careful detailed estimates, justify itself on its own merits, as affording facilities for making transportation more profitable.

When the railroad man is looking at a transportation problem from the constructive and maintenance standpoint, he has in mind the crystallized experience of some 70 years of steam railroad practice that has resulted in the development of railroad equipment along certain lines, which, generally speaking, are rather conservatively maintained. It may be well to recall the fact that the steam locomotive of the present day is in its essentials practically the same machine that was developed by George Stephenson; that is, it comprises a horizontal multitubular boiler with a fire-box at the rear and smoke-stack at the front, and the wheels are propelled by a direct-coupled, high-pressure engine, which increases the rate of combustion of the fuel by discharging its exhaust into the smoke-stack. Similarly, the passenger car has been developed from the old omnibus. A departure from some previously recognized form is often found good, but there is nevertheless considerable resistance to change. In justice to steam railroad men, however, perhaps it should be said that opposition to new forms is not likely to be so great because of radical difference in themselves, as because of the great cost of keeping on hand a line of repair parts entirely different from those which their present historic equipment obliges them to carry in stock. This, of course, pertains more especially to rolling stock and track material. Most railroads have worked up a line of standard parts of equipment, and the Master Mechanics' and Car Builders' Associations have coöperated extensively to promote the use of these standards upon all the railroads, and there will naturally be considerable opposition to any disturbance of such standards. Although the electrical equipment will necessitate, for its own maintenance, the addition of a considerable quantity of repair stock, it should not without good reason be permitted to change any previously existing standard that it is desirable to keep. On the other hand, there may be some very fundamental reasons for changing existing standards in order better to accommodate certain electrical features. An instance of this upon a certain railroad was the adoption of a new shape of splice-bar, specially rolled, to accommodate a heavy rail-bond underneath it, upon a section where some new track was to be laid; while the objection of another railroad to increasing the diameter of a motor-car wheel on account of the additional size of tire that would have to be carried in stock eventually resulted in the retention of an electric motor originally adopted for a lighter car. At first the motor had been thought too small for the increased duty which was to be imposed upon it, but was found to be adequate when fitted with suitable means for increasing its capacity, thus satisfying the desire of the railroad for the maintaining of standards in its equipment and at lower cost.

The question of clearances has often been most perplexing, particularly as regards the location of either third-rail or overhead trolley construction. The stationary features pertaining to the right of way, and the dimensions of moving equipment, must not be allowed to interfere with each other. The third-rail sometimes conflicts with bridge-gussets on the one hand, or with hopper-bottom coal-cars on the other. The use of third-rail also makes more necessary the elimination of highway grade-crossings, and requires careful attention to the protection of the public at station platforms. Low overhead bridges conflict seriously with trolley construction, particularly when high voltage is desired.

High-tension trolley construction introduces, among other problems, the purely mechanical one of providing suitable warning signs or ticklers for trainmen on the tops of freight cars; these must not only be light enough not to injure brakemen, nor damage the trolley mechanism on moving equipment, but must also be heavy enough to withstand the blows they receive from the trolley without being broken or rendered useless.

Either type of construction may require special and often expensive arrangements at drawbridges. The civil authorities in cities sometimes arbitrarily insist upon placing high-tension lines underground, which is always expensive. Telegraph and telephone lines have to be protected from mechanical and electrical interference. These are a few of the characteristic problems that arise with each electrification scheme, but solutions of them do not appear on the mathematical curve sheets with which professional papers are sometimes illustrated.

Looking again at cars and locomotives, the steam railroad man will commonly take his standard coach as the point of departure, and suggest at the outset that it be equipped electrically practically as it stands. Here it is entirely in order to remark that the main object of electrification is to facilitate traffic. The car bodies themselves should be built with that end in view, in order to get the full benefit of the superior type of power. The object to be attained affects the dimensions of the vestibules, doors, and seats, as well as the length of the car, and even the form of roof of the car may be altered from standard types without detriment to passengers, if external conditions make it desirable. Suburban service is the type of service that admits of the greatest modifications in this respect; and that car is likely to be the most popular with the patrons of the road which is so built as to enable freer ingress and egress of passengers, a matter which should not be lost sight of where there is competition between different lines to be taken into account. It is no little tax upon the engineer's ingenuity to get the best results in a new development, and still conform to the general lines of conventional car designs, some features of which have been based upon rules and practices primarily imposed for the greater safety of the traveling public.

Coming now to locomotive design, perhaps the most fundamental advantage which an electric locomotive has over its steam predecessor is greater mechanical simplicity, particularly as regards translation of the tractive effort from the motor to the wheel-rim. The absence of reciprocating parts is advantageous to a high-speed electric locomotive for passenger service, because of the lessened vibration of the locomotive itself, and the greater diminished wear and tear on the track. In the case of a slow-speed electric freight locomotive, the uniformity of tractive effort in hauling heavy train loads is a very desirable feature, particularly at starting. The tendency towards simplification and elimination of reciprocating parts has caused the concentration of great weight at a less height above the rail than is usual for a steam locomotive of equivalent power; and this lowering of the center of gravity is not without its effect in running conditions at high speed, particularly upon a curved track. Steam locomotive men regard a high center of gravity as advantageous rather than detrimental, because its longer leverage from the top of the rail, which is the fulcrum, eases the side-thrust against the rails, due to whatever centrifugal force or lateral vibration there may be. So confident are steam engineers that this is a cardinal point of superiority that they express a desire to see electric locomotives so built that the essential difference between a steam and electric locomotive will consist in the replacement of the boiler upon the locomotive frame by an electric motor, in order to keep the center of gravity at something like its present height. If electric locomotive designers in this country keep as clear of the use of side-rods in the future as they have in the past, there does not seem to be much chance for increasing the distance of the center of gravity from the track to the height it frequently reaches with a steam locomotive; but in Europe some of the latest and most successful electric locomotive designs show a tendency to set the motors above the driving wheels, two motors being used to drive three axles through side-rods. The mechanical excellence of workmanship of these locomotives has been attested by some of the foremost electrical engineers of this country who have seen them. Whether or not the tendency of this design will persist, will depend upon how applicable this method of coupling proves to be to the loads and speeds met with in this country.

The latest developments in American locomotive practice as exemplified by machines actually in commerical operation or under test show three types: first, that of which the driving-wheel base is rigid, as in the case of the New York Central and the St. Clair tunnel locomotive units, the former having pony wheels, the latter none; secondly, the articulated or bogie-truck type, with two large driving trucks pivoted to the locomotive body, each truck carrying a large motor on each axle; and a third type, now being tested by the Pennsylvania Railroad, which is built upon a locomotive frame of standard type, borne at the rear upon the outside journals of two large driving axles, each carrying a 500-h.p. motor, the forward end of the frame being carried upon a four-wheeled bogie truck generally similar to that commonly used with the American or Atlantic type of steam locomotive. This particular sample is designed primarily for single-phase traction, and a transformer is carried over the bogie truck but not at a relatively great height above the rails. The superstructure of each of these locomotives is a steel-plate cab or enclosure housing the engineman and the control apparatus, but in no way approaching the weight of the boiler mounted upon the frame of the steam locomotive. The third type above described has appealed to steam locomotive men as conforming more nearly to their preconceived ideas of locomotive construction, but it remains to be seen whether American designers will work out any method that will result in further lifting the center of gravity along the lines followed by the latest European practice.

Railroad electrification invariably raises questions of safety to the traveling public. Both the third-rail and the trolley are frequently described in the daily press as "deadly". The fact that on a third-rail system a bad short-circuit can take place without blowing the station circuit-breakers, which have to be set for heavy overloads, sometimes results in serious blockades. When the damage is done it is usually expensive, and takes time to repair. In the case of a high-tension trolley system only a small leak is sufficient to cause a short-circuit, and the amount of actual damage done thereby is trifling. Such troubles as may be developed by short-circuits are generally not of long duration; whatever wires or cables are burned in two are burned quickly, and clear themselves promptly. With a high-tension system there is no possibility of confusion between an overload and a short-circuit.

Another feature of the question of safety involved is the dependence of a large number of electrical transportation units upon one power station as opposed, in the case of steam transportation, to an equivalent number of entirely independent units. It is perfectly possible for a disabled electric train to ground or short-circuit the line in its own vicinity in a manner that will prevent other trains from approaching. This is not the case with steam locomotive trains, as the terrible record of steam train collisions bears witness. Generally speaking, the combination of electric propulsion with the block-signal system for protecting trains has not been developed, though in the early days of the art the matter was occasionally brought forward as additional argument in behalf of electrification. The paramount desire to keep all traffic in motion has militated against the idea of permitting the disabled train or line-section to hamper in any way the movement of other trains on other sections. It is evident that there are possibilities along this line, particularly in the case of high-tension systems, that can justly receive further consideration, because with the smaller currents flowing in high-tension systems, control of them at a distance is relatively easier than in the case of the heavier currents in low-tension systems.

We now come to a phase of the question which in the writer's opinion is probably the most complicated and least understood of all; namely, the standpoint of the railroad operator or transportation superintendent, and his organization, upon whom the railroad depends for maintaining its earning power. It hardly need be said that the transportation man has it in his power either to make or mar the earning capacity of a railroad, and no matter what facilities for increasing transportation capacity are furnished by the management, the duty of making them pay dividends devolves upon the operating department. The business of a railroad being primarily transportation, and transportation being the special function of the operating department, we here come in contact with the highly trained specialist, upon whom falls the burden of getting the traffic over the road whether it be level or hilly, straight or crooked, single or double track.

It is conceded by all, that the great thing to be desired in a railroad of given proportions is capacity for train-movement. The capacity of a double-track road is stated to be in general, about four times that of a single-track road, general conditions as to grade and location being equal; but as more than seventy-per cent. of the railroad mileage of the country is single track, the most universal problem of increasing track capacity by electrification will apply to single-track rather than to double-track lines. This, of course, excepts terminal and suburban conditions, but includes the majority of mountain railroad conditions where double-tracking is sometimes a physical impossibility.

On the greater proportion of single-track railroad mileage, trains are handled by the telegraphic train-order system under the control of train dispatchers. On some railroads, however, block-signal systems are installed to facilitate the movement of trains, as much time is thereby saved by each train in getting the right to pass from one block to the next. According to a report by the Interstate Commerce Commission, published about March 1, 1907, the total number of miles of railroad lines which had any block-signal system at all was 143,615, of which 48,743 miles was actually equipped and operated by some form of block-signal system. Of this 48,743 miles, 6,826 were operated by the automatic system and 41,916 by one of the several forms of non-automatic system. Of the mileage controlled by the automatic system, 2,032, or somewhat under one-third, was single track. Of the lines controlled by non-automatic signals, 33,585 miles were single-track lines, making a total of 35,617 miles of single-track railroad in the United States controlled by some form of block signal. The total mileage of single-track lines in the United States is estimated at about 200,000, so that about 17.5 per cent of the total single-track mileage is controlled by block signals at the present time. Inasmuch as the operation and maintenance of a block-signal system is undoubtedly cheaper per mile of road than the total annual cost that would be incurred by electrifying, it would appear that the first step in increasing the capacity of a road is to establish a suitable block-signal system. Thus from a practical standpoint the mileage of track where electrification could profitably be considered under present conditions would be greaty reduced; but when the increased capacity created in any instance by a block system has been fully utilized, a further increase is still possible by the use of electric motive power.

Engineers familiar with the interurban trolley development of the past ten years are aware that most lines of this type dispatch their trains very largely by the telephone system. Generally speaking this method works very well, though on the more highly developed systems it is combined with some of the features that have been standardized by the rules of the American Railway Association, and adopted by practically all the steam railroads. It must be remembered, however, that conditions on trolley roads are somewhat different from those on steam roads. The vast majority of the trains are light passenger trains of one car each, stops are of shorter duration, and the speed of all trains is more nearly uniform. The distance between turnouts is less. The penalty of a wreck due to misunderstanding or miscarriage of orders is, generally speaking, much less with the average interurban trolley road than with the average steam railroad; and trolley railroad operators are correspondingly more willing to run the risks incidental to dispensing with the system of transmission of train orders, which experience has shown to be necessary on steam railroads. The meeting points are generally much nearer together, and a block system of any kind would cost relatively more to maintain and operate in proportion to the business done than is the case with steam railroads. At least there seems to be some such motive preventing the universal adoption of signal systems by trolley roads. In any event, it is not at all convincing to a steam railroad man to point out to him the apparent ease with which trains at frequent headway in opposite directions are handled with single-track trolley roads, as a reason why the same course should be adopted by steam railroads in order to increase the rapidity of train movements. Although it is undoubtedly true that the telephone is used extensively as an adjunct to standard methods of dispatching steam-railroad trains, railroad managers generally do not seem disposed to supersede the method developed by the use of the telegraph, except in the relatively small amount of mileage protected by automatic block signals.

Whether the telegraphic train-order system or one of the other systems of block signals be used, the rules governing the operation of trains on steam railroads are very rigid. The telegraphic train orders, emanating from the train dispatchers' office, must be signed by the recipient and the signature telegraphed back to the dispatcher, who then replies "complete" to the various operators to whom he has sent the message as fast as their replies come in. An order restricting the rights of a superior train is more rigidly safeguarded in this respect than an order increasing the rights of an inferior train; and a superior train must receive and reply to its orders before any can be given to the inferior train. Much time may be and often is thus consumed, which may restrict considerably the capacity of a line to handle traffic. Another rigid type of rule is that requiring an inferior train to clear the time of a superior train at a meeting or passing point by not less than five minutes. This holds whether a train-order system or a block-signal system be used. This five minutes' clearance is frequently, for special reasons, increased to ten minutes and often to twenty minutes, thus placing the inferior trains at a still greater disadvantage. Instances of this kind occur when some especially fast express train is operated, where, to insure the greatest possible degree of safety, twenty minutes clearance is provided. The fastest high-speed "flyers" of the present day are thus protected, to the greater safety of the passengers, but to the disadvantage of freight trains. Two such flyers, one in each direction over a road per day, will thus cut down the current of slower traffic over the whole road to the extent of at least forty minutes per day, and frequently more. If an inferior train cannot make an intended siding in time to allow for the required clearance it is obliged to wait on a nearer siding and lose the time required for the superior train to cover the distance between the two sidings, plus any extra time which the superior train may have been delayed. One such delay is more than likely to lead to another, and so the delays pile up into hours during the run intended to be made in ten or twelve hours. If traffic is dense, and sidings far apart, such delays become very serious, and besides the delay to freight, and disappointment and inconvenience to shippers and per diem charges on cars, there is added the overtime due to the employes, which increases the operating expenses. It seems to the writer that conditions of this character are not taken into sufficient account as having a bearing on the subject of electrification for increase of track capacity; and something more than the ability to accelerate rapidly and maintain higher speeds must be given consideration in estimating the increase in the net schedule speed of train movement that at first sight may seem directly to result from the substitution of electricity for steam.

One item peculiar to steam operation which causes delays is the stopping for water. The frequency for such stops will depend both upon the weight of the train, and the grade of the road. Stopping for water sometimes adds to the delays from other causes that have previously held up a train; but for any particular problem the effects of stops for water should be considered separately from stops for other purposes. Where combined with a stop for some other purpose, no marked gain is effected by eliminating the necessity for taking water, unless perhaps three or four engines were to take water in succession.

A case was recently cited of a single-track road in a mountainous country where double tracking would be a very expensive proposition, this road having a heavy traffic in both directions, loaded ore cars coming down and empties going up. It was found in operation that the easiest way to get the traffic over the road was to make every siding a meeting point, that is to say, the road was practically full of trains. The only way of increasing traffic on such a line other than by double-tracking would be to increase the speed of all trains in the same proportion. This might seem feasible enough by electric motive power, but then arises the question whether the increase in speed that could be thus obtained would be sufficient to enable an increase in the daily traffic that would pay a dividend on the total cost of electrification. This would be an excellent instance of a concrete case in which other things than motive power costs alone, of steam and electricity, would have to be considered. In a case of this kind, the capacity of a single-track road would be limited by the speed of the slowest train.

The task of working out the results in such a case is necessarily complicated and would require nothing less than a close study of all the conditions on the ground. The fact that it is impossible to generalize upon the capacity of single-track roads for train movement, renders it equally impossible to generalize upon the applicability of electric motive power thereto in comparison with steam. It is necessary to pick out a concrete case and estimate all the features in detail, just as it is in order to properly gauge the economic value of any other engineering enterprise. It is obviously unscientific to advocate wholesale electrification as a means of increasing capacity, when the capacity can be increased more cheaply, as it sometimes can, by the introduction of a block-signal system, or when the capacity of a piece of road even when equipped with a block-signal system, could not be increased in practical operation to a point that would enable enough more ton-miles per day to be run off at a lower cost per ton-mile, to show a saving in total annual cost.

The writer is a firm believer in the value of electric motive power as a means of increasing a railroad's earning capacity, but begs to suggest that in the future more professional papers be devoted toward giving concrete illustrations in a manner that will carry some conviction to the minds of the progressive and highly trained specialists in transportation, who are doubtless willing to be convinced if the subject can be dealt with in a manner that appeals to their practical experience in the operation of trains.

A paper presented at the 223rd Meeting of the American Institute of Electrical Engineers, New York, December 13, 1907.

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THE RATIO OF HEATING SURFACE TO GRATE SURFACE AS A FACTOR IN POWER PLANT DESIGN

BY WALTER S. FINLAY, JR.

Power plant design, in its modern development, is controlled solely by the specific application of general laws modified and moulded to suit special requirements. To attempt the construction of a comprehensive ruling from the results of a particular line of investigation in some particular plant, and then to advise the general use of such ruling as conducive to economical operation, would cause confusion, possibly resulting in a wholesale rejection of the good with the bad. However, the value of specific results and their publication lie in the opening up of a line of technical thought, or in adding information to some subject, from which specific deductions or particular application may be made.

The results obtained in the investigation, which was primarily the foundation of this paper, should be looked upon merely as specific, but whose bearing upon the general subject by means of a general development, may be of value, particularly in certain new phases of plant design.

As a fundamental and almost initial point of attack in the comprehensive subject of steam power-plant design, the ratio,

$$\frac{\text{heating surface}}{\text{grate surface}}$$

has been a value fixed from the beginning of results of commercial usage, and the expression of the same in empyrical formulas or figures suited to the requirements of this or that designer, builder, or manufacturer.

A summation of practice from early engineering times to values developed by the most modern idea, gives a great range to this ratio; namely, from the extreme value as advised by Dalton in 1839 of ten to one, to modern values up to seventy to one used, not only in locomotive, but even in power-plant practice. Of course the primary object in view has been the adaptation of values to produce the maximum useful effect; but the question now arises as to whether or not "maximum useful effect" is not being interpreted as maximum economical efficiency with reference to fuel only, as a primary consideration, and with an undue subordination of total plant costs. By total plant costs are meant, of course, the combined fixed charges resulting from interest on plant investment, depreciation, taxes, etc., and operation and maintenance charges.

Properly to investigate the subject in its particular applications would require an extremely tedious and complicated study of innumerable individual requirements; but for a general survey assumptions based upon commonly accepted values will suffice to direct the attention to the point involved.

Assuming a plant first cost of $125.00 per kilowatt; the equipment, including turbo-generators, boilers equipped with stokers, with, say, sixty to one ratio, the following relative costs may be assumed:

Total cost per kilowatt.............	$125.00	100 %
Building " "	43.75	35 %
Boilers " "	6.875	5.5 %
Grates " "	1.75	1.4 %
Piping " "	5.625	4.5 %
Coal-handling apparatus per kilowatt.....	2.30	1.84%
Balance of equipment..................	64.70	

The value of the building as assumed might be considered low, particularly in the case of a turbine plant; the boiler cost is, possibly, average; grates high—a stoker valuation; the piping value is about average.

Assuming as a fair value for determining fixed charges: interest on investment, 5%; depreciation, 6%; taxes and insurance, 1%, then the total fixed-charge rate would equal 12%.

Upon bases of load-factor and charges, a curve has been drawn showing the relative value of the fixed charges over a range of factor variation from approximately 3% to 100%, in the case of the plant as assumed. (Curve A, Fig. 1.)

To determine total charges, the variation of maintenance and operation charges, relative to load-factor, must also be considered. It is rather difficult to assume this curve, as conditions in this respect vary rather widely. However, Curve C, Fig. 1, has been drawn through points located by comparative results obtained in actual cases of operation. The shape of the curve will practically be constant for any figure which may be assumed, and its relation to the general results will be such that the value of the principle involved will be unaffected.

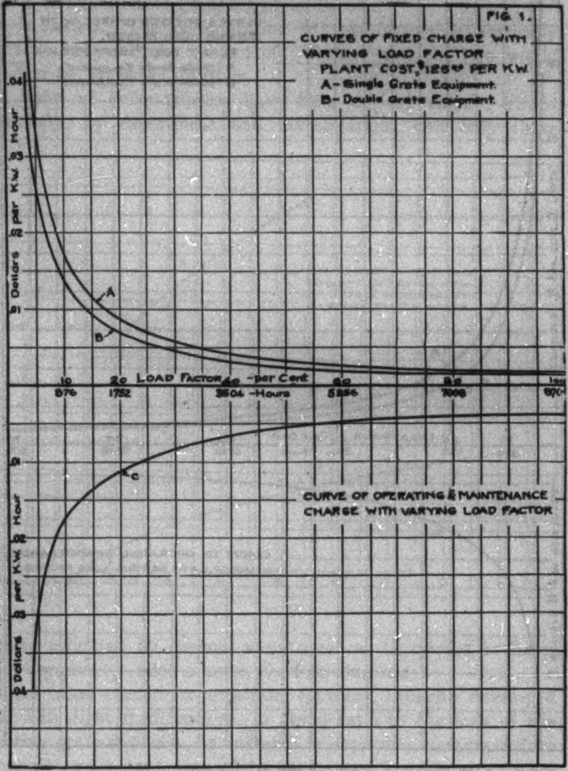

FIG. 1

The sum of the ordinates between the two curves gives total charges per kilowatt-hour.

In a reconsideration of the plant design as affecting first cost, the natural method of procedure is to consider separately each item involved.

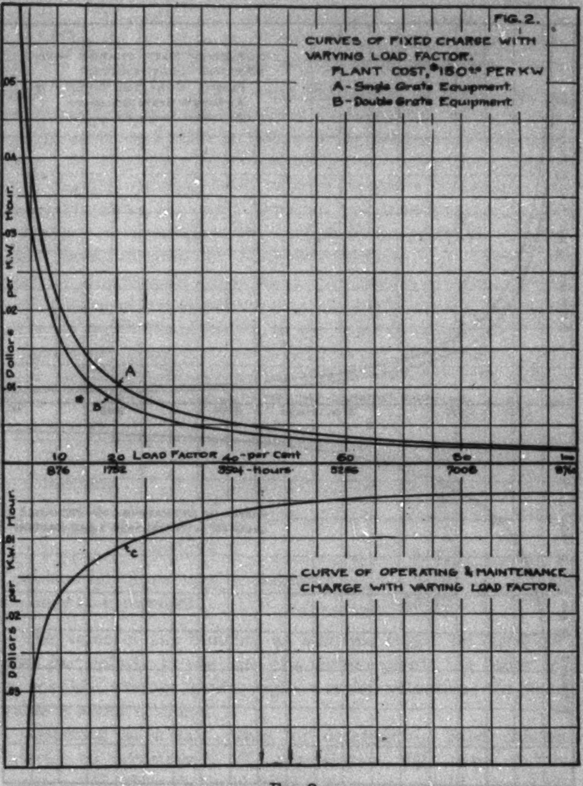

Fig. 2

1. *Building.* In turbo-generator plant design, it is a generally accepted rule that total plant dimensions are controlled by boiler-room dimensions; that, for instance, a diminution in

the actual size of the boiler room may be accompanied by a proportional diminution in the size of the turbine-room, the output remaining the same. The methods of accomplishing such results are perhaps various, change in size of units, difference in type, closer grouping of units, etc.

2. *Boilers*. The consideration of this feature is naturally interlinked with the subject of "*Grates*" and the two would better be discussed together.

Rules of boiler-practice have been derived chiefly, if not entirely, by experiment and investigation; and only those rules validated by general acceptance can be quoted as bases for argument. Such a law is the following one:

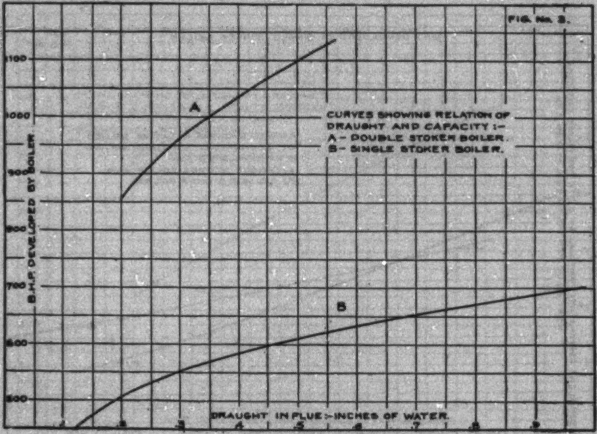

FIG. 3

All other conditions remaining constant, capacity developed is, with slight modifications, in direct ratio to the area of the active grate surface. An increase in capacity—heating surface remaining constant—caused by an increase in grate area, is accompanied by a loss in economical evaporation, due to the increased temperature of the escaping gases.

This loss in economy is the fundamental factor which must necessarily be the object of a careful study, involving the complete investigation of the heat interchanges taking place in a boiler. The research work of such men as Newton, Péclet, Joule, and Rankine, together with recent investigation, has not, as yet, produced sufficiently definite and authoritative results, which may be used as bases of rational calculation in this regard. Under normal conditions of present boiler-practice, estimates of loss vary from practically zero to as much as 15% fuel economy for an increase of 100% in boiler capacity.

Lately, however, the opinion has been advanced that considerable increase in capacity can, without great sacrifice in economy, be obtained by proportional increase in grate area. This idea is based upon the possibility that combustion and heat distribution and transfer could be much improved under the new conditions, when in increasing the grate area careful attention is given to details of design most conducive to these features. Other conditions being favorable, and with a belief in the correctness of this theory, a change was made in the design of eighteen of the boiler furnaces in the Fifty-ninth street plant of the Interborough Rapid Transit Company. See Fig. 7. Such a design gave the possibility of operating within the range of the original single-stoker boiler together with the higher range of the double stoker.

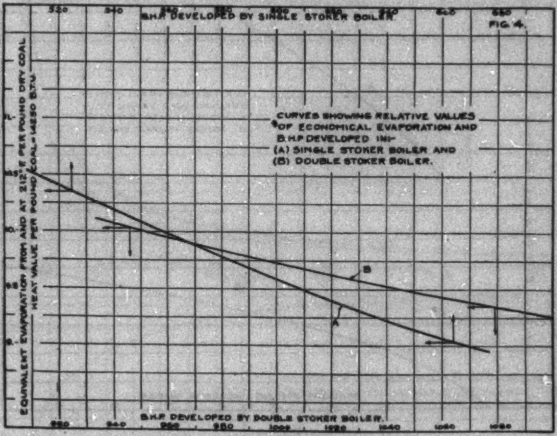

Fig. 4

The second stoker installed; that is, the one beneath the mud-drum as shown in Fig. 7, has an area of 80% of that of the original stoker. Certain features in the construction of the plant prevented installation of a larger size. A detailed description of points in the design are unnecessary, save to call attention to the fact that the lower stoker is constructed practically within a so-called "Dutch oven" and whatever is conducive to good combustion is provided for therein. The curve shown on Fig. 8 is given as corroborating this fact. Operation of these stokers has shown that such is practically done with but little more complication than existed in the single type.

Tests to determine the comparative economical operation of the double and single stokers show results as given graphically in Figs. 3, 4, 5, and 6. The curves in Figs. 3 and 4 are self-explanatory. Fig. 5 shows a curve plotted upon the values as determined by curves in Fig. 4, this curve being indicative of the fact that operation with the double type was as economical in fuel values, as the single type increased in boiler capacity approximately seventy-one per cent. In the curves in Fig. 6 is shown the fact that the economical loss for an increase in rating of 80%, as proportioned to the increase in grate area, varied between two and three per cent.

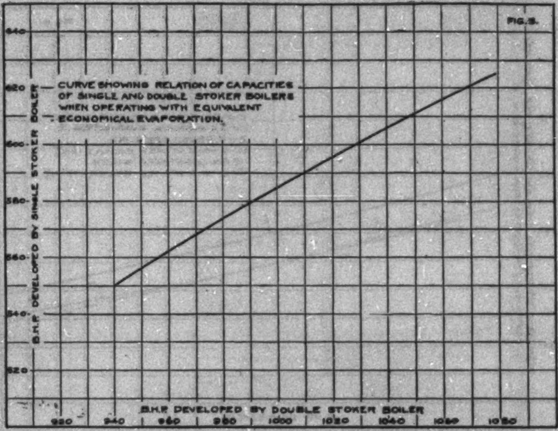

FIG. 5

To summarize the results of these tests: it has been made evident that in this particular case double-stoker operation covers the entire range of single-stoker operation and adds an increase of capacity proportionate to its larger grate surface with but slight loss in economy, and that the increase of 71% in capacity is accomplished with no loss in economy.

With these results as a basis, let it be assumed that boiler capacity is increased in ratio to increase in grate surface with but little loss of economy. This view might be further strengthened when consideration is taken of the possibilities of economizer practice, the increase in saving, by proper design, being high in ratio to extra cost involved.

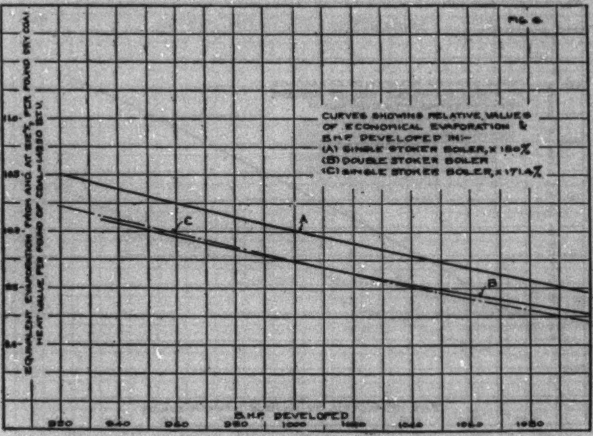

FIG. 6

To return to the consideration of the items under the power plant whose first cost has been assumed to be $125.00 per kilowatt, the next point is:

Piping. In the case involved, the cost of steam piping between boilers and manifolds, plus boiler-feed piping, plus boiler blow-down piping, has alone been considered. With any change in number of boilers, capacity remaining the same, the cost of piping will vary in the same ratio times a factor due to change in size of pipe.

Coal-handling apparatus. Fixed plant capacity would seem to demand fixed cost of coal-handling apparatus, but the pro-

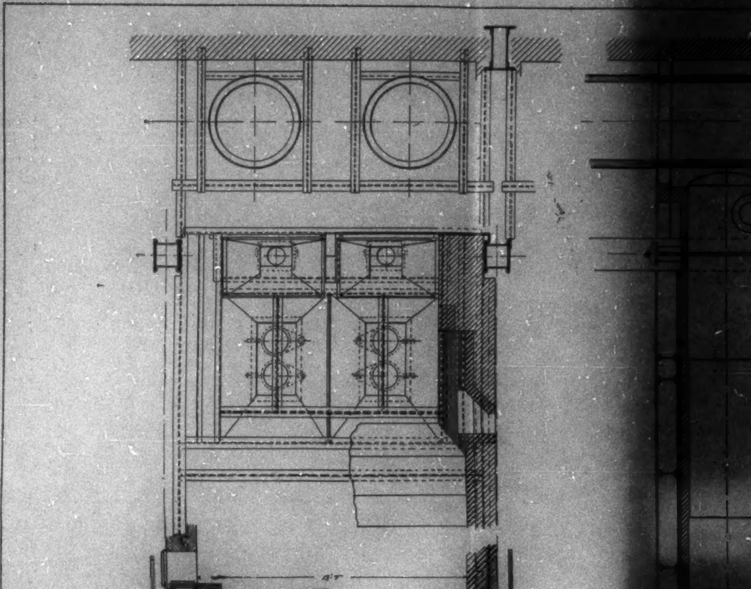
13'7"
BOILER FLOOR ELEVATION + 17'3"
5'0"
7'6"
5'0"
7'6"
5'0"
13'6½"
TOP OF RAIL OF ASH CAR TRACK
LOOKING SOUTH

Fig.

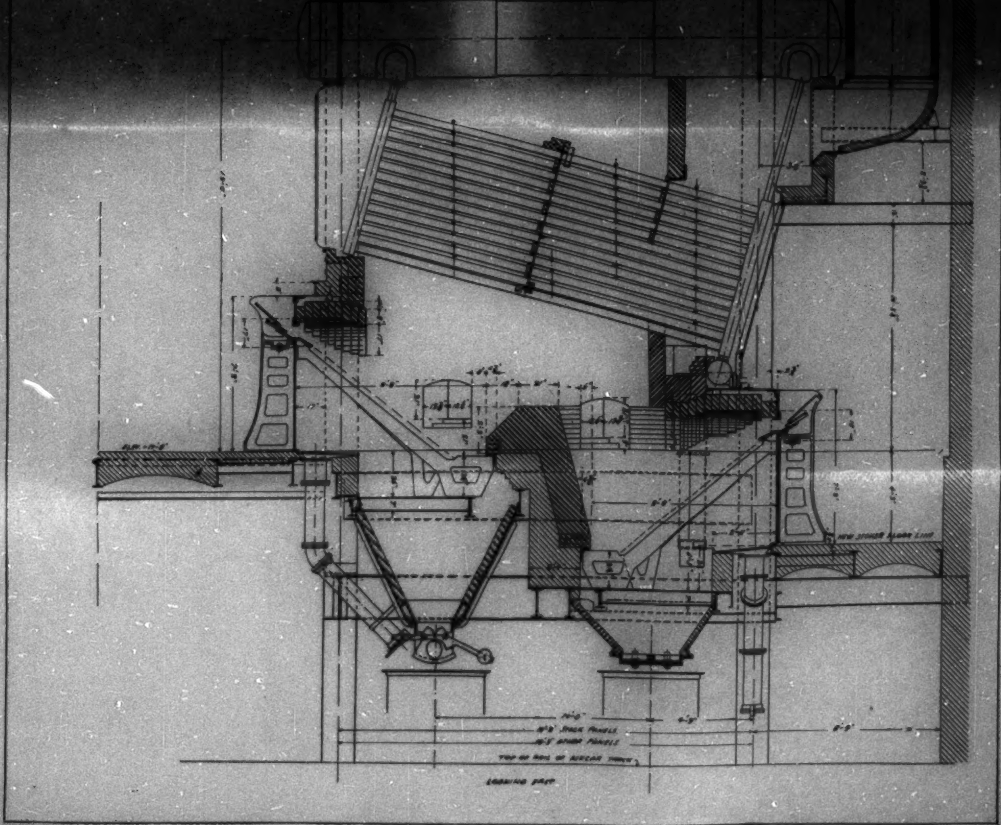

FIG. 7.

NEW STOKER FLOOR LINE
No 8 STACK PANELS
No 5 STOKER PANELS
TOP OF RAIL OF ASHCAR TRACK
LOOKING EAST

portionate value of the conveying apparatus is so large that when any change is made affecting the length of carry the total system cost will be raised or lowered, although not in direct ratio to such change.

Effect of change of ratio:

$$\frac{\text{heating surface}}{\text{grate surface}}$$

Suppose that in a reconsideration of the plant design, it is decided to cut in half the ratio of heating surface to grate surface by the use of double grates or stokers under boilers of the same rating. Plant output is to remain the same. A tabulation of the costs as revised would be as follows:

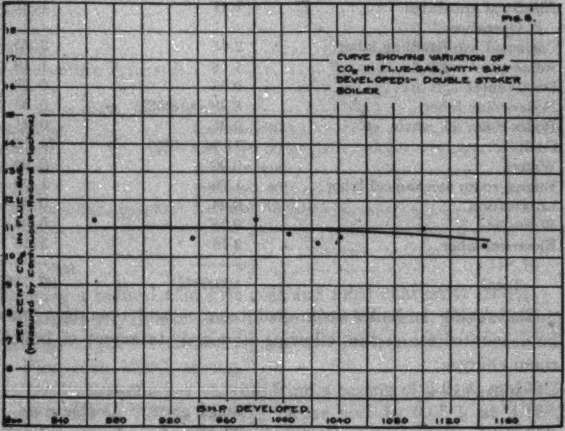

FIG. 8

	Per kilowatt
Building (reduced 40%)	$26.25
Boilers (reduced 50%)	3.438
Stokers (remain same)	1.75
Piping (reduced 40%)	3.735
Coal-handling apparatus (reduced 15%)	1.955
Balance (remains same)	64.70
	$101.828

A curve (B Fig, 1) is plotted upon this new basis.

Summation: Plant first cost and fixed charges, each reduced 19.6%.

The next consideration is that of the effect of such changes upon plant maintenance and operation charges. Properly to discuss this, the following tabulation based upon the figures given by Mr. H. G. Stott in his paper on "Power Plant Economics" will furnish a means of comparison:

Maintenance:	Single grate		Double grate
Engine room mechanical	0.64%		0.64%
Boiler room	5.40 − (16%)	=	4.54
Coal- and ash-handling apparatus	0.68		0.68
Electrical apparatus	1.41		1.41
Operation.			
Coal- and ash-handling labor	2.65		2.65
Removal of ashes	1.18		1.18
Dock rental	0.93		0.93
Boiler-room labor	8.38 − (18.5%)	=	6.83
Boiler-room oil, waste, etc	0.21		0.21
Coal	71.94 + (3%)	=	74.10
Water	0.90		0.90
Engine-room mechanical labor	1.70		1.70
Lubrication	0.44		0.44
Waste, etc	0.38		0.38
Electrical labor	3.16		3.16
Total	100.00%		99.75%

The saving in boiler room maintenance and operation may be accounted for in the following itemized statement of boiler-room charges:

Maintenance.	Cost	
	Single grate	Double grate
Boilers	29.5%	14.75%
Economizers	2.78	2.78
Furnaces	17.29	17.29
Stokers and stoker engines	40.68	40.68
Boiler feed-pumps	5.42	5.42
Boiler feed-piping	2.20	1.10
Boiler blow-off piping	0.44	0.44
Water supply piping	1.52	1.52
Total	100.00%	83.98%
Operation.		
Water-tenders	20.82	10.41
Stoker operators	38.09	38.09
Assistant stoker operators	15.49	15.49
Stoker oilers	2.54	2.54

Economizer oilers and cleaners	5.84	2.92
Boiler feed-pump men	5.08	5.08
Boiler cleaners	10.41	5.21
Miscellaneous labor	1.73	1.73
Total	100.00%	81.47%

Thus with changes as noted, the decrease in maintenance and operation would be 0.25%, the curve for same practically coinciding with Curve C, Fig. 1.

A second set of curves based upon a plant cost of $150.00 per kilowatt is shown in Fig. 2.

Plant cost per kilowatt	$150.00	100%
Building	60.00	40
Boilers	8.25	5.5
Stokers	2.25	1.5
Piping	6.75	4.5
Coal-handling apparatus	2.63	1.75
Balance	70.12	

Same plant double stoker.

Building	(reduced 40%)	$36.00
Boilers	(reduced 50%)	4.13
Stokers	(remain same)	2.25
Piping	(reduced 40%)	4.05
Coal-handling apparatus	(reduced 15%)	2.24
Balance		70.12
Total		118.79

showing a reduction in first cost and fixed charges of 20.8%.

Summary. In the case of the $125.00 plant, the following savings might be effected by use of double grate:

First cost, 19.6% saving.

Total plant charges varying from a saving of 5.64% at 100% load-factor to 7.54% at 50% factor and to 9.65% at 4.16% factor (365 hours per year).

In the case of the $150.00 plant,

First cost, 20.8% saving.

Total plant charges vary from about 7.06% saving at 100% load-factor, to 9.26% at 50% factor to 11.51 at 4.16% factor.

Thus summarized, the remarkable effect that the grate area and heating surface ratio, when furnace design is carefully considered, may have upon plant first cost and total annual costs, should certainly place this particular feature well up in the list of subjects for careful investigation, and make it a point of primary and fundamental consideration in advanced design.

DISCUSSION ON "THE RATIO OF HEATING SURFACE TO GRATE SURFACE AS A FACTOR IN POWER PLANT DESIGN", AT NEW YORK. DECEMBER 13, 1907.

Chas. E. Lucke: Comparing the two curves of Fig. 4 it would appear that for an equivalent evaporation of 9.25 lb. of water per pound of coal, the ratio of boiler horse powers with double and single stokers is as 1100 is to 638 or about 1.72, with 9.5 equivalent evaporation the ratio is as 1046 is to 609, or about 1.72, with an equivalent evaporation of 9.75 the ratio is as 996 is to 582, or about 1.71. It thus appears that when operating this boiler at capacities 1.71 times as great with double stoker as for single, the equivalent evaporation, and, therefore, the boiler efficiency, is in nowise altered. At the same time referring to the curve for single-stoker operation there is reported for 512 h.p. an evaporation of 10.50 lb., which fell to 9 lb. on an increase of boiler horse-power to 670. In this case, therefore, an increase of boiler horse-power from 510 to 670, a ratio of capacities of 1.31, the efficiency or equivalent evaporation decreased in the ratio of 10.5 to 9; or the efficiency for the higher capacity is to the efficiency for the lower capacity as 9 is to 10.5, or, approximately, 0.86. An increase of boiler capacity in a given boiler is to be obtained by burning more coal primarily. From the preceding it would appear that burning more coal under this boiler with a single stoker gave a continuous drop in efficiency; also from the other curve an increase in the burning of coal on two stokers gave a decrease in efficiency continuously, but strangely enough, a very material increase in the coal burned per hour operating double versus single, sufficiently great to increase capacity to 1.7 its original value, gave no decrease in boiler efficiency. Why is it that with a single stoker an increase of capacity from 1 to 1.3 lowers the efficiency from 1 to 0.8, while increase of capacity from single to double stokers from 1 to 1.7 does not decrease the efficiency at all.

With increase of coal burned under the single stoker, the curve falls continuously and then breaks, starting again at a high point at the beginning of the double-stoker line, along which it again falls. It would seem as if these two curves should join and be continuous, and the fact that they do not, warrants an investigation into the causes. All of the general discussions of boiler efficiency seem to concentrate the conditions for efficiency, and with some degree of reason, on two prime variables; one entering into the structure, the other the operation. The first is the ratio of heating surface to grate surface, and the other is the rate of combustion per square foot of grate surface. With a view to determining how far the ratio of heat surface of itself, independent of other things, might effect boiler efficiency, one of the students at Columbia examined some 300 boiler tests that seemed most authentic and plotted, as in Fig. 1, boiler efficiency against the ratio of heating surface to grate surface.

From these data, it appears that the boiler efficiency lies between 45.4 per cent. and 84 per cent., while the ratio of heating surface to grate surface lies between 14 and 89. The disposition of the points is such as to prevent any conclusion in the form of curves or law of relation, as they do not group themselves in any definite way, but are deposited over what has often been called "a shot-gun diagram", and not a very good one at that. It would thus appear that the ratio of heating surface to grate surface cannot of itself fix boiler efficiency, however much it may seem to be rationally related to it.

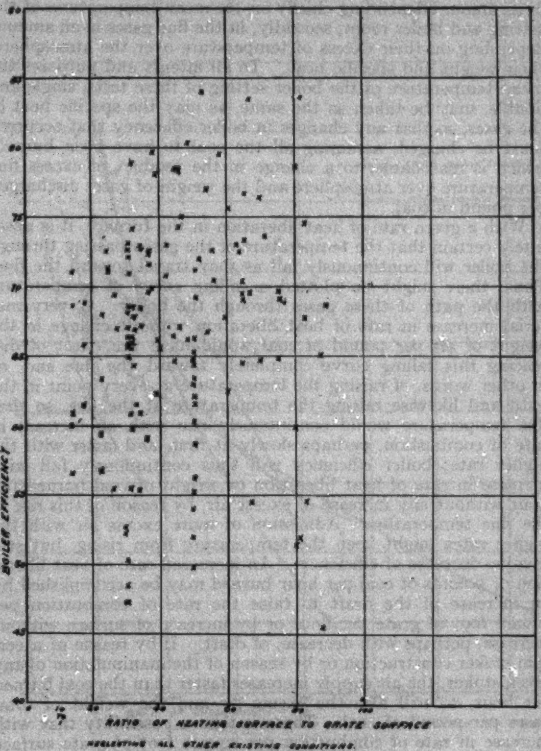

FIG. 1.

The phenomena taking place in a boiler are really quite simple. Any question of boiler efficiency resolves itself into an examination of these phenomena in an attempt to trace the losses. Neglecting all insignificant losses and assuming all coal to be burned, a boiler has an efficiency of less than 100 per cent. because some of the heat is liberated in the fire escapes; first, by radiation in an amount depending chiefly on the mean temperatures of the setting and boiler room; secondly, in the flue gases in an amount depending on their excess of temperature over the atmosphere, their weight and specific heat. To all intents and purposes the mean temperature of the boiler setting of these tests, single and double, may be taken as the same, as may the specific heat of the gases, so that any changes in boiler efficiency that occurred must be charged, assuming all the coal to have been burned, which is reasonable, to a change in the product of excess flue temperature over atmosphere and the weight of gases discharged per pound of coal.

With a given rate of heat liberation in the furnace, it is absolutely certain that the temperature of the gases passing through the boiler will continuously fall as they travel toward the flue. Thus, there might be plotted a falling curve of temperature with the path of these gases through the boiler. A very material increase in rate of heat liberation without change in the weight of air per pound of coal would have the effect of displacing this falling curve completely toward the flue end, or in other words, of raising the temperature at every point in the path and likewise raising the temperature at the flue, so that flue temperature would continuously rise with an increase in rate of combustion, perhaps slowly at first, and faster with the higher rate; boiler efficiency will thus continuously fall with increase in rate of heat liberation or weight of coal burned per hour without any increase of excess air, by reason of this rise in the flue temperature. Admission of more excess air with the higher rates might keep the temperature from rising, but still involve decrease of efficiency. An increased rate of heat liberation or pounds of coal per hour burned may be accomplished by an increase of the draft to raise the rate of combustion per square foot of grate per hour or by increase of surface without increase, perhaps with decrease, of draft. If by reason of a certain stoker construction or by reason of the manipulation of any given stoker, the air supply increases faster than the coal burned per hour, so will also the excess air and the weight of total gases per pound of coal. There is thus a possibility that with increase in rate of combustion per square foot of grate surface there may be also an increase in weight of gases per pound of coal by an increase of excess air, which would tend to decrease the boiler efficiency.

An examination of the results of this test does not indicate from the curve for either the single or the double stoker which factor was more potent in decreasing boiler efficiency with increase of coal burned per hour—the flue-gas temperature or the excess weight of gases, but comparing the double-stoker curve with the single and finding thereby that the same boiler efficiency corresponds to the same rate of combustion

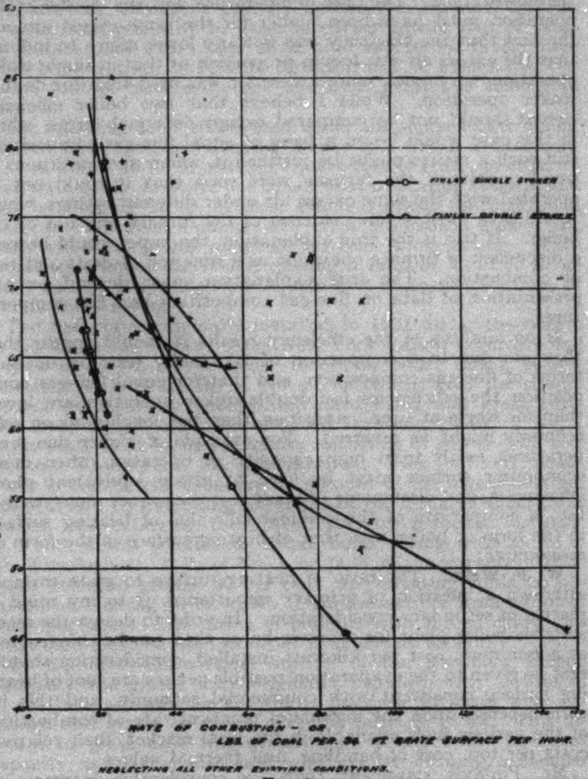

FIG. 2.

per square foot of grate, it would seem that the excess-air factor was more potent than the flue-gas temperature factor. It is inconceivable to me that increasing the coal burned per hour from 2370 for the single stoker to 4100 for the double stoker, or

1.74 times as much, which corresponds to 9.25 evaporation for both cases, there should have been no change in the boiler efficiency if the weight of gas per pound of coal was the same in both cases, especially as with the higher rate the time of contact between gas and boiler tubes is very much less than for the lower rate. The flue temperature for the double-stoker operation must have been higher for the same excess air, and the fact that the efficiency was not any lower seems to indicate that the excess air was less in proportion or that in single-stoker operation, very much more excess air was used than for double-stoker operation. While I believe that two boiler efficiency curves should not be compared except on equal terms, which in this case would be on a basis of equal flue-gas composition, still such a course might be justified if, under the conditions of usual operation, the furnace were such that it could not be operated with the same excess air under different ratings, which would be a most severe criticism of the furnace and not of the boiler. If this is the true explanation, the paper would become a discussion of furnace operation as a function of draft and rate of combustion. The true explanation must depend on the presentation of data on flue-gas composition and flue temperatures.

If on analysis of the efficiency results it should appear that they are due to a comparison of two boiler tests on unequal terms of flue-gas composition, and that for equal flue-gas composition the efficiencies for double-stoker operation are lower than for single at equal capacities, then the conclusions on cost economy might be reversed. For example, if higher flue temperatures result from high capacity of operation, then more economizer surface must be used to attain equivalent plant efficiencies, and discussions of plant cost economies must resolve into a comparison of the commercial value of heating surface in the form of boiler with that of heating surface in the form of economizer.

W F. Wells: The ratio of heating surface to grate surface, although a question of primary importance, is to my mind a matter of secondary consideration. In order to design the most suitable boiler plant for a power house that can be constructed at a minimum cost per kilowatt installed, consideration should first be given to the evaporation possible per square foot of heating surface consistent with commercial economy; and this in turn depends upon the maximum practical rate of combustion of the various fuels available in the local market, their relative costs per ton, cost of handling, and thermal values.

Mr. Finlay's statement that "a considerable increase in boiler capacity can, without great sacrifices in economy, be obtained by proportional increase in grate area" is applicable to most power plants, because until very recently, power house engineers have endeavored to obtain the greatest economies possible from boilers by proportionally increasing the heating surface, so that the average boiler of to-day will give but little more than rating when fired with the so-called " steam coals ". In other words, most boilers, as installed on land, are rated on a basis of 10 sq. ft. heating surface per horse-power and will evaporate but 3.5 pounds of water per square ft. of heating surface, whereas, in marine practice double this amount, or 7 lb. of water, can generally be evaporated per square foot of heating surface; and with closed stoke-hold and forced draft, three times boiler rating, or 10.5 lb. of water, can be evaporated per square foot of heating surface and even greater is sometimes possible.

The following table shows that under the single stoker boiler, referred to in the paper, having a *ratio of* 1 : 56, it is necessary to burn about 20 lb. of coal per square foot of grate, in order to evaporate 3.5 lb. of water per square foot of heating surface, and that by burning 25 lb. of coal, which is about the maximum that can be burned commercially on a mechanical stoker, the boiler will develop only about 20 per cent. above rating. With two stokers under the boiler, making a ratio of 1 : 31, 7 lb. of water can be evaporated per square foot of heating surface, or double boiler rating.

The flat grates originally installed in 1901 under the boilers at the Waterside Station of the New York Edison Company had a ratio of 1 : 74, and in order to obtain boiler rating, it was necessary to burn 35 lb. of No. 3 buckwheat coal per square foot of grate, which necessitated hard firing and great care. The same output could be obtained by firing 28 lb. of No. 1 buckwheat, or 31 lb. of a mixture, consisting of 20 per cent. soft coal and 80 per cent. No. 3 buckwheat. This, however, meant a loss in commercial economy on account of the higher cost per ton of fuel. By extending the fronts of the furnaces under these boilers, and enlarging the grates, thereby reducing the ratio to 1 : 59, it was possible to obtain boiler rating with 25 lb. of No. 3 buckwheat, 22 lb. of No. 1, or 24 lb. of the mixture. With those extended grates, 50 per cent. above rating could be obtained by burning 40 lb. of No. 1 buckwheat per square foot of grate per hour. This firing is possible with forced draft, but great care must be used in order to maintain economy.

In the Sixty-Sixth street station of the Brooklyn Edison Company the grates were originally installed with a ratio of 1 : 68, but last summer the fronts on these furnaces were extended and grates enlarged, giving a ratio of 1 : 53. This increase in grate area was utilized not so much for increased capacity as to give increased economy by burning a cheaper fuel. The economy actually effected by this increase in grate area amounted to 14 per cent. in cost of evaporating 1000 lb. of water.

At our Gold street station, the grates as originally contracted for three years ago were at a ratio of 1 : 76, but before installing the furnace, fronts were extended, thereby reducing the ratio to 1 : 59, and under the boilers installed in 1907 by moving back the bridge-wall, this ratio was still further decreased to 1 : 52. Under boilers proposed for 1908, this ratio has been reduced to 43.

With this ratio of 1 : 43, almost double boiler rating can be obtained, or 7 lb. of water per square foot of heating surface, can be evaporated by burning No. 3 buckwheat, and double rating probably exceeded by burning No. 1 buckwheat or a mixture. This ratio would have been made less but for the physical impossibility of handling a deeper fire box.

It must not be assumed that the least ratio practicable is the best, as there is a possibility of making the grate too large for the heating surface. In addition to the disadvantage of the loss of economy, due to excessive flue temperatures already mentioned, there is the necessity of banking boilers at times of light load, and the loss of time and labor necessary again to bring the fires into condition for steaming.

Walter T. Ray and Henry Kreisinger (by letter):* Perhaps the first inkling that something was wrong came when a number of operating engineers in various places began to explore the interior gas passages of water-tube boilers with thermocouples, and found large dead corners. We have carefully explored many boilers and have never failed to find room for improvement, provided only that it is mechanically feasible to insert gas baffles so as to cause the gases to reach a greater portion of the heating surface, at the same time permitting the gases to travel over the whole surface with at least as high an average velocity as before.

This latter point is important, for practically no benefit would come from inserting baffles such as would cause the gases to flow into dead corners, if at the same time the gas velocity over the old portion of the heating surface were proportionately reduced. The velocity of the gases over, (or past, or along), the heating surface is the active feature which determines how much heat will be imparted to the surface. other things being equal. If the velocity of gas be doubled, the amount of steam produced per second will be nearly doubled. For a fuller discussion of this matter we refer to the Geological Survey's bulletin entitled " A Study of Four Hundred Boiler Tests ".†

The possibility of greatly increasing the rate of heat transmission into boilers will be apparent when it is considered that the amount of heat which can be passed through a thin metal plate is enormous. The heat-resistance of the metal in the case of boilers is insignificant, perhaps ordinarily much less than, $\frac{1}{100}$ of the whole; the seat of resistance is in the layers of scale and soot, and, most of all, probably, in the films of gas adhering to the soot and of steam and water adhering to the scale. If these are reduced in thickness by increasing the velocities of the streams of gas and water rubbing against them, the rate of heat transmission will be greatly increased. This is not mere theory, but has been experimentally demonstrated on laboratory models and on large boilers.*

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* We wish it distinctly understood that the United States Geological Survey is in no way officially committed to any of the opinions advanced hereafter. Presented with the permission of the Director of the United States Geological Survey.

† Bulletin No. 325, United States Geological Survey, Washington, D.C.

The great increase in capacity in the case cited by Mr. Finlay was undoubtedly due to the increased velocity of the hot gases over the heating surface of the boiler. By burning 80 per cent. more coal, the weight of hot gases generated per second was increased by the same amount. In passing this increased weight of gases through the same boiler the velocity was increased by the same percentage, resulting in an increase of 80 per cent. in capacity.

Mr. Finlay has made only a beginning in working his boilers harder. The Interborough Rapid Transit Company has verified the conclusions experimentally reached mathematically by Professors Reynolds and Perry of England. It is our personal opinion that the boilers under consideration could probably stand five passes instead of three, and that perhaps some other minor changes would be beneficial.

Mr. Finlay's device of putting two stokers under one boiler accomplished the burning of more coal without working the combustion chamber any harder; that is, without increasing the velocity of gases from grate to tubes. Such an increase would have resulted in lessening the time available for the combustion of certain gases. It will be noticed that the distance from the old grate to the entrance into the tubes is only about one third the distance from the new grate to the same entrance; it is therefore likely that the gases from the new stoker are more completely burned, and so it is not surprising that on heavy loads the evaporation per pound of coal was as high as at lower loads on the old stoker alone. The point we wish to emphasize is, that the efficiency of the boiler as a heat absorber is practically constant and independent of the rate of working. The boiler will do its part in meeting increased demands for steam.

In the Jamestown Exposition Plant of the Geological Survey is a 210 h.p. boiler which has been so re-baffled as to cause the gases to pass through the tubes twice instead of once. They pass through a smaller cross-section, nearly twice as far, at a higher average velocity, with the result that about ten per cent. more heat is absorbed, accompanied by no reduction in capacity when using the same draft. When the draft is raised and the boiler made to produce about twice its rated amount of steam, it still retains nearly all of its increased efficiency. Here is a case of greatly increasing the output at a slight cost and at the same time increasing the economical evaporation per pound of coal.

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* See "The Nature of True Boiler Efficiency," by Walter T. Ray and Henry Kreisinger, September 18, 1907, Western Society of Engineers, Chicago.

We see no reason why boilers can not be so designed as to yield several times as much steam per square foot of heating surface as they now do, and with a considerable increase in economical evaporation. One thing seems inevitable—complete resort to forced or induced draft, or, better still, to both.

W. L. Abbott (by letter): Mr. Finlay assumes the cost of a plant to be $125.00 per kilowatt and of this the cost of the building is 35 per cent. or, $43.75, and also that the size of the building is determined by the number of square feet of heating surface in the boilers. He therefore proposes to re-design the plant, using only half as much boiler heating surface, but worked to double the former capacity, thereby effecting a saving of $23.58 per kilowatt in the cost of the plant of which amount $17.50 is due to a reduction of 40 per cent. in the size of the building.

While the foregoing assumptions may have been correct a few years ago, they certainly do not apply to more recent designs for turbine plants using large generating units. In these designs the size of the building is not determined by the number of boilers any more than it is determined by the number of turbines, and the cost of the building, which is about $15.00 per kilowatt, is divided about equally between the boiler room and the rest of the plant. The reduction of 40 per cent. in the cost of the building incident to a reduction by one-half of the boiler heating surface will therefore be applied only to a $7.50 boiler room and not to a $43.75 power house building.

Again, Mr. Finlay allows an additional loss of only 3 per cent. of the fuel when he doubles the rating of a given boiler. This assumption is probably correct for a boiler having an ample economizer, but in the case of a boiler not so supplemented, the additional fuel loss would undoubtedly be as much as 10 per cent., and it should be stated here that the figures given above for cost of boiler room do not allow space for an economizer.

We now have the following approximate figures for power house costs:

With boilers of standard rating...............	$96.00
" " double " ".................	$93.00

Both of these prices are without economizers.

Taking these new figures and calculating the data for curves similar to those given by Mr. Finlay, it appears that the total cost of current output will be practically the same in both cases, regardless of the rating at which the boilers are worked.

A. Bement (by letter): It is rather remarkable in the tests described by the author, how nearly constant final efficiency is in steam generation with one and two stokers, and this may be partially explained by the fact that the proportion of the usual type of water tube boiler is such that only a part of the tube surface is acted upon by hot gases, and if a larger volume is forced over the boiler, as would occur with two stokers, their relatively greater body, demanding more space, will extend to portions of the boiler which were practically unused with a single stoker. This has been illustrated elsewhere.*

Referring to Fig. 7 which shows an elevation of boilers and stokers in the Subway power plant, it would appear that a furnace roof has been improvised by the insertion of a baffle between the tubes of the two lower rows of the boiler in the rear. If this be true, it leaves the lower row of tubes exposed to the heat from both stokers for about five-sixths of its length. I would inquire if it has been possible to operate these boilers to to any considerable extent without destroying the tubes of this bottom row by overheating. Even if they have been able to stand such an amount of work, this design of furnace could be very much improved by the use of encircling tiles which are usually made in lengths of 12 in. as have been elsewhere described.† This would not only reduce the amount of work required of the bottom tubes, but would furnish a more satisfactory roof than an inserted baffle does.

F. V. Henshaw (by letter): It may be well to point out that as neither heating surface nor grate surface has fixed value for different designs and conditions, they should be considered in connection with specific cases, and the ratios of the two compared with due regard to all the features of the furnaces and boilers in the different cases. A trifling change in the baffles can greatly alter the value of the heating surface in water-tube boilers, and numerous other variables are obvious.

In designing boiler-plants we have to provide for two distinct operations: first, the chemical operation of burning fuel; secondly, the physical operation of conveying the heat generated to the boiler water. The apparatus for performing these operations is supplied by independent makers. These makers are at times opposed in their requirements. The boiler designer being anxious to secure a high rate of evaporation and rapid circulation, may wish to apply the fire too directly to the boiler, with resultant imperfect combustion and production of cinders and smoke. The fuel value of discharged cinders and smoke is not great, but the deposit from them on tubes reduces the value of the heating surface, and, when emitted from city chimneys, they have a large " injunction and fine " negative value.

The boiler shown as Fig. 7 is a well known type with a slight change in the baffles. The front furnace is standard, whereas the rear furnace has a longer combustion arch. The grates are much farther below the tubes, and the tubes directly above the grates are covered by a baffle which deflects the flames toward the boiler-front. One would expect the rear furnace to be considerably more efficient, to produce less smoke or cinders, and to require a rather higher draught pressure than the front furnace. We have here, therefore, something more than a simple case of added grate area.

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*Transactions American Society of Mechanical Engineers, Vol. XXVI, p. 626.

† Journal Western Society of Engineers, Vol. XI, p. 752.

In the curves given, the single stoker doubtless refers to the front furnace. Additional comparisons of each furnace operated singly would be interesting.

It seems to me that the estimate for cost of boilers is somewhat too low, on account of the greater cost of settings for the double-furnace boiler.

W. S. Finlay (by letter): It is evident that the discussion has been productive of possibly more valuable experimental results than are contained in the paper itself, and to attempt to reply to each and every feature of the very long and elaborate criticisms, would be absolutely out of the question. What may be said in reference to these discussions, is said with due respect and recognition of the greater knowledge and experience possessed by the gentlemen whose work determines the value of the subject in hand.

Possibly it was unfortunate that more emphasis was not given to the fact that the specific solution of the problem of increased efficient combustion, namely, the double stoker, was not proffered as a general or sole solution, but was quoted as merely one form, convenient and satisfactory in the case to which it was applied. Neither did the writer desire to give any specific value to the ratio, simply wishing to emphasize the importance of its careful consideration under attendant conditions.

With reference to Dr. Lucke's criticisms, which are chiefly from a theoretical standpoint, a reply should be given from a similar basis. A careful study of the discussion shows that there has been practically but one point brought up, this point being repeated in a number of different ways. In form, the discussion is interrogative, tending to throw a doubtful light upon the experimental data referred to in the paper. A declarative form might be stated as follows:

1. Operation under double-stoker conditions should theoretically conform to operation under single-stoker conditions. With increased total combustion, and increased capacity, economy should decrease regularly, if expressed graphically, in a single continuous curve, whether such increase in capacity be accomplished by increased combustion upon a single stoker, or upon a double stoker.

2. Boiler efficiency is conditioned upon two variables:

a. Ratio of heating surface to grate surface.

b. Rate of combustion per square foot of grate surface.

The question has thus been reduced to a study of: first, that which actually determines boiler efficiency; secondly, the form in which this efficiency varies.

It is a self-evident fact that a diagram, such as the "shot-gun" diagram, based upon results of three hundred tests under all sorts of conditions—boilers, combustion chambers, etc.—is of little or no value, and useless so far as it bears upon theoretical investigation.

The rate of combustion must be recognized as a factor in the "unit" efficiency under practical conditions, but as to its effective value so far as the boiler proper is concerned, it would, in the light of recent investigation, seem highly probable that boiler efficiency decreases but little under conditions of increased rating.

Merely to consider two factors determining boiler efficiency, namely: 1. The ratio of heating to grate surface—primarily a specific feature, which can not be generalized—and, 2. The rate of combustion, would be obviously to neglect certain most elementary and fundamental features in design.

It is inadvisable to attempt completely to discuss all factors entering into boiler and grate efficiency, particularly as certain new features in theory and experiment indicate that knowledge of the subject is not at all complete. However, a summary of recognized factors from both theoretical and practical points of view will serve to indicate the relative effective value of each upon the efficiency of the boiler when considered as a unit consisting of boiler proper, furnace, and grate. Thus, for any given set of conditions, unit efficiency will depend upon the following factors:

1. Grate design, a factor involving in practice relative values of air-space, adaptability to grade of fuel, ease of handling in process of cleaning, with attendant effect due to admission of excess air, etc.

2. Furnace design, which involves complete combustion of gases, and transmission of the same to the heating surface when at their maximum temperature.

3. Method of air supply, which must naturally be considered together with the preceding factors.

4. Boiler design, which may be sub-divided as follows:

a. Relative exposure of heating surface to heat radiation from fire and furnace walls.

b. Design of heating surfaces in relation to direction of quantitative flow of gases.

c. Design of baffling as effective upon flow of gases, with due regard to the effect of such baffling upon soot accumulation, and "dead" space; also to direction of circulation in boiler.

d. Boiler design in respect to rapidity of circulation of water.

5. Boiler proper, maintenance and operation. This factor includes cleanliness in inner and outer surfaces of tubes and drums, together with the condition of all parts of the unit. Operation includes care and handling of fire, together with manipulation to obtain best combustion and lowest practicable flue-gas temperatures.

A number of other governing factors might be quoted, but for purposes of comparison the above will suffice.

A comparison of conditions existing in the single- and double-stoker boilers as influenced by changes in certain of these factors, will serve to explain the apparent discrepancies which

Professor Lucke calls attention to. In the change from single to double stokers, the only factors vitally affected, are:

1. Furnace design, in which case the new design undoubtedly favors a more complete combustion of gases, a point in favor of increased efficiency.

2. Grate design, the possibility of increasing combustion per square foot of heating surface without a tendency to force excess air through the fire.

3. Increased exposure of heating surface to radiation from the fire-bed.

4. Greatly increased volume of flow of hot gases; larger portion of the heating surface becoming active, and dead spaces and eddy currents of gases decreasing in number and effect. Heat convection to heating surface is increased by reason of greater speed of gas circulation.

5. Boiler operation is improved by reason of the fact that increased water circulation tends to lessen the formation of scale, as well as improved heat convection inside of tubes.

The above summation of changes in conditions, with their effect upon the unit efficiency, tends to show that curves plotted upon bases of efficiency and rating for the single-stoker boiler and the double-stoker boiler need not be identical, the one a continuation of the other. These curves would necessarily be distinct and individual for each set of conditions.

It is to be noted, in the particular case of the efficiency curves given, that the decrease in efficiency for increase in rating seems to be rather rapid. To lessen the slope of these curves, the self-evident solution is to provide such draught or air-supply conditions that forcing of fires would not be accompanied by excess air supply or undue disturbance of fires.

A move in this direction, with apparently successful results, has already been taken; but the fact remains that the double stoker must retain the all-round higher grate efficiencies accompanying combustion at a lower rate per square foot of grate surface, together with improved furnace conditions. The feasibility of obtaining efficient high boiler output, with due consideration of total plant charges and costs, makes the double-stoker simply one device to obtain certain results, its choice to be based upon ruling conditions.

Mr. Wells bases his entire discussion upon a premise whose value is exactly the point which originated the question brought up by the writer. He makes the statement:

> Consideration should first be given to the evaporation possible per square foot of heating surface consistent with commercial economy; and this in turn depends upon the maximum practical rate of combustion, etc.

This is just a re-statement of heating surface and furnace relation. However, having made this statement as the fundamental, his development of the subject has unfortunately been merely along lines of hitherto accepted methods of increasing boiler capacity without any consideration of the latest phases of development giving consideration to the possibilities latent in heating surface efficiency.

The discussion by W. T. Ray and H. Kreisinger is peculiarly valuable in view of the fact that it incorporates results of most recent investigation. The writer considers it a most practical verification of what has been said in reply to Dr. Lucke's discussion as well as of the original paper.

It is evidently a misinterpretation of the writer's thought that Messrs. Ray and Kreisinger have emphasized the point of fixed valuations to the ratio of heating to grate surface. The writer fully realizes that such a fixed valuation could not be generally applied, the purpose in view being more particularly a careful consideration of furnace and heating surface relation. as applied to each specific case in the light of results such as have been realized by the very investigations of the United States Geological Survey.

Mr. Abbott objects to considering the size of the boiler plant as practically the determining factor in the size of a plant building. Conservative design, as exemplified in nearly every recent plant of importance, has been on the parallel plan, it being almost uniformly an accepted rule that consideration must be given to plant growth and extension, in addition to uniformity, as necessary to simple operation. The turbo-generator in point of permitting extreme flexibility in adapting turbine room size to boiler room size has been an additional incentive to the development of this system.

Replying to Mr. Bement's first question in reference to the life of the bottom row of tubes, the writer would say that operating results for a period of about three months show most satisfactory results in this regard. Improved circulation and evenness of heating of these tubes result in improved cleanliness and little wear. Mr. Bement's statement in reference to increased utilization of heating surface in the case of the double stoker seems to corroborate the reply to Dr. Lucke's discussion.

Albert A. Cary: Mr. Cary presented a careful analysis of fuel combustion, and the relative distribution of heat losses throughout the process of such combustion, for the particular purpose of emphasizing the need of deliberation and care in the design of furnace and grate in their relation to the boiler. In support of his position, Mr. Cary cited numerous examples and facts gathered during years of wide experience.

J. P. Sparrow: It sems to me that undue prominence is given to the matters of grate area; if the question were the proper relation of boiler heating surface to maximum station output as affecting station design and operating costs, then the matter of grate surface becomes one of obtaining the necessary capacity at the maximum efficiency.

In the ratio of square feet of heating surface to kilowatt capacity there are quite wide variations in practice—variations of from 5 to 1 to 10 to 1; there are also similar variations in the evaporation per square foot of heating surface, every-day practice showing examples of from 2.5 to 8 lb. for land service, and as high as 10 or 12 lb. for marine work.

In the ratio of grate area to heating surface, common practice varies between the limits of 75 to 1 to 35 to 1. In central station service where variable loads are the rule, these variations in heating surface and grate area bear on two points—the economical evaporation per square foot of heating surface, and the economical rate of combustion per square foot of grate. Large grate areas have been advocated for many years, nearly always, however, from the standpoint of capacity.

The performance quoted of a single stoker giving a boiler output of 610 h.p. and an equivalent evaporation of 9.5 lb. represents a combined furnace and boiler efficiency of 64.4%. A comparative performance of the double stoker gives a boiler output of 1050 h.p. for the same equivalent evaporation. To compare with results obtained from other installations, I would quote a performance of a single stoker of the same size and design under a boiler of the same heating surface, of a boiler output of 1070 h.p. with an equivalent evaporation of 11.2 lb. or a combined efficiency of 74.5%. This capacity was obtained with a flue draft of 0.85 in. Mr. Finlay shows only 750 h.p. from a single stoker with same draft.

Taking the curves in Mr. Finlay's paper as a basis, his single stoker developing 600 h.p. burned coal at the rate of 19 lb. of coal per square foot of grate, his double stoker at the rate of 18 lb. at 1000 h.p. while the installation referred to above burned coal at the rate of 28.6 lb. developing 1070 h.p.

On a test of a marine boiler built for the cruiser Cincinnati with a ratio of heating surface to grate surface of 41.7 to 1, coal was burned at a rate of 59.75 lb. per square foot with equivalent evaporation of 9.63 lb. or an efficiency of 64 per cent.

The New York Edison Company has for some time been conducting tests of high rate of combustion of soft coal under forced draft, and have on test burned at the rate of 44 lb. of coal per square foot of grate with a boiler output of 1300 h.p. and a combined efficiency of 73 per cent. With anthracite coal under forced draft burning 24 lb. per square foot, 1,070 h.p. was developed with a combined efficiency of 69 per cent. The evaporation per square foot of heating surface of these various tests and the efficiencies are:

Mr. Finlay's single stoker..........	3.4 lb.	64.4 per cent.
double "	5.7 "	64.4 "
Waterside single "	5.7 "	74.5 "
Waterside forced draft "	7. "	73. "
" " " anthracite	7. "	69. "
U. S. S. Cincinnati..................	9.6 "	64. "

In electric lighting stations where the storm peak demands may be from 60 to 100% above normal, it is most convenient, and I believe most economical, with the commonly accepted ratios of grate to heating surface, to operate boilers at about 15% above rating, relying on the ability to force evaporation to meet the sudden load demands. If this operating routine is correct, then increased grate areas are opposed to good economies. It is practically impossible to burn fuel at low rates of combustion on large grate areas with reasonable economies. We all know the difficulties experienced in checking excess air when operating with a ratio of grate to heating surface of 1 to 60, how much more difficult it will be to operate with ratio of 1 to 32 at the same boiler output.

A very large number of tests conducted by The New York Edison Company with boilers designed with ratios of 10 sq. ft. of heating surface to one boiler horse power have shown conclusively that while there is a falling off of combined efficiency at high rates of evaporation, this decrease of efficiency is not at all serious if the higher rate is maintained only at time of peak load.

The crux of the matter lies in an increase in rate of combustion, this bearing the same relation to construction costs and fixed charges as Mr. Finlay's increase of grate surface. An evaporation of 6 lb. of water per square foot of heating surface is not unreasonable, and as against 3.4 lb. allows a decrease in boilers of 43 per cent. A comparison on this basis with the figures in Mr. Finlay's paper would show:

Maintenance	Evaporation per square foot of heating surface		Evaporation per square foot of heating surface
	3.4 lb.		6 lb.
Boilers	29.5 %	43%	16.82%
Economizers	2.78		2.78
Furnaces	17.29	20%	13.84
Stokers	40.68	20%	32.55
Boiler feed-pumps	5.42		5.42
" " piping	2.20	43%	1.25
" blow-off "	0.44	43%	0.19
Water piping	1.52		1.52
	100.00%		74.37%

or 74.37 : 100 as against Mr. Finlay's 84 : 100.

Operation	3.6		6 lb.
Water tenders	20.82	43%	11.87
Stoker operators	38.09	43	21.72
Assistant stoker operators	15.49	43	8.83
Stoker oilers	2.54	43	1.45
Economizer oilers	5.84		5.84
Feed pump men	5.08		5.08
Boiler cleaners	10.41		10.41
Miscellaneous	1.73		1.73
	100.00%		66.93%

or 66.93 : 100 as against Mr. Finlay's 84 : 100.

As Mr. Finlay has said, the value of specific results obtained lies in their adaptability to existing conditions. These results to be of value must be fairly indicative of results obtainable under normal operating conditions, and I fail to see the warrant for the conclusions drawn on the basis of the results quoted.

J. E. Moultrop: I understand that the installation described by Mr. Finlay was brought about by reason of the necessity of more steam from a boiler house built as large as the location permitted, and completely filled with boilers. Also, that previously to the installation of the double grates, these boilers were run at about their rating, 600 h.p., and that the original grates had an area of 100 sq. ft. These data, together with the evaporation curve in Fig. 4, indicate that the maximum coal consumed per square foot of grate per hour was about 21 lb., not a large amount compared with the consumption of some other large stations. As the curves indicate an ample draft, the natural question is, why was not more coal burned on the original grate? An inspection of the other curves indicates that this could have been done, and practically the same capacity obtained from the original grate as is now obtained from the two grates, but the economy would fall off appreciably.

If this be true, the solution of the problem is not necessarily more grate area under the same boiler. There is nothing in the paper to indicate that any change was made in the heating surface or in the travel of the gases across the heating surface, so it may be assumed that this part of the boiler remained unchanged and that all improvements were made in the furnace. The cross-sectional elevation of the boiler shows two noticeable changes in the furnaces; the ignition arch on the new furnace is longer than in the old, and the combustion chamber is much larger. The new boiler appears to be almost twice the size of the old one. These two modifications are decided improvements, and should be large factors in the improved operation of the boiler. It does not follow that it was necessary to build a second furnace under this same boiler to obtain these improvements, because the original furnace could be re-designed on similar lines, and if necessary a considerably larger grate could be placed in one furnace.

The proposition to reduce the size and cost of the boiler plant is a step in the right direction, but in so doing the utmost simplicity should be maintained, especially in the large stations of to-day. Possibly the scheme adopted at the Interborough station was the best that could be devised in an existing plant for a reasonable cost, but it does not follow that this design is a good one to adopt in laying out a new station.

A vertical-header boiler is more compact, and with 18-ft. tubes, 14 high, will be some 3 ft. shorter and take about 41 sq. ft. less floor space than the inclined-header boiler. Here is a real saving in building space with no disadvantages. Such a boiler can be equipped with as large a single grate as may be conveniently installed under the rear end of the boiler, with the gases passing in the usual way through the heating surface. In other words, install the vertical header boiler in a similar manner to the Interborough boiler with the original furnace omitted. This arrangement incorporates all the real advantages of the double-grate plan with none of the disadvantages of the latter, except possibly one. Both of these plans require a tile roof on the lower row of tubes immediately over the fire, which may prove troublesome to maintain.

A paper presented at the 223d Meeting of the American Institute of Electrical Engineers, New York. December 13, 1907.

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AN EXHAUST STEAM TURBINE PLANT

BY HENRY H. WAIT

At the Wisconsin Steel Company's Mill at South Chicago the turbine utilizes the exhaust steam from a reversible engine which drives the blooming rolls. The steam passes first to the receiver which takes out the shock of the puffs of steam, thence to the steam accumulator or "regenerator", and from there to the turbine and condenser. The general layout of the plant is shown in Fig. 2.

As this is the first plant of this character to be installed in this country, it was subjected to an elaborate series of tests by Mr. A. U. Leonhauser, the chief engineer of the Wisconsin Steel Company, and Mr. F. G. Gasche, mechanical engineer of the Illinois Steel Company. Besides testing the turbine equipment, the arrangement offered an opportunity to test the steam consumption of the primary engine by making a temporary change in the piping, so that the exhaust was led directly to the condenser without passing through the turbine. Mr. Gasche has already published an account of the various tests, giving very interesting continuous indicator diagrams of the engine and charts of the roll-train resistance, etc.*

Primary engine. This is a 42 by 60 double-cylinder engine, of the rolling-mill type. When in normal operation the engine rolls about 19 ingots per hour with 21 passes per ingot, stopping and reversing after each pass with a short interval for the starting of a new ingot, so that it is stopped or practically idle 20% of the time during the cycle required for turning out an ingot. There are other frequent stops for the ordinary manipulation of the mill which last from a few seconds to several minutes.

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*"Power" June 1907.

The average i.h.p. while the engine is actually running is 1010, and, if the total work per hour were distributed evenly over the hour, the average i.h.p. for the hour would be 820. Figuring back from the total steam consumption gives 64 pounds of steam per average i.h.p. for the hour, or 54 pounds during the running period. This large consumption is readily understood when we consider that the engine takes steam for practically the full stroke when starting the passes, and is running on very light load most of the rest of the time. Of course the horse power and especially the torque runs up enormously when the rolls first take hold of the ingot.

FIG. 1

Receiver. This is the vertical drum shown on the left of Fig. 3. When the engine is exhausting directly to the atmosphere and is taking steam at nearly full stroke, the puffs of steam shoot a long distance up in the air and make a noise like a number of big locomotives puffing in unison. The receiver is to relieve the accumulator of the strains and disturbance which would occur if the puffs went directly to it. The receiver consists of a tank with a number of baffle-plates and is provided with drains for water and oil. At the top of the receiver, between it and the vertical exhaust-pipe, used when desired to exhaust directly to

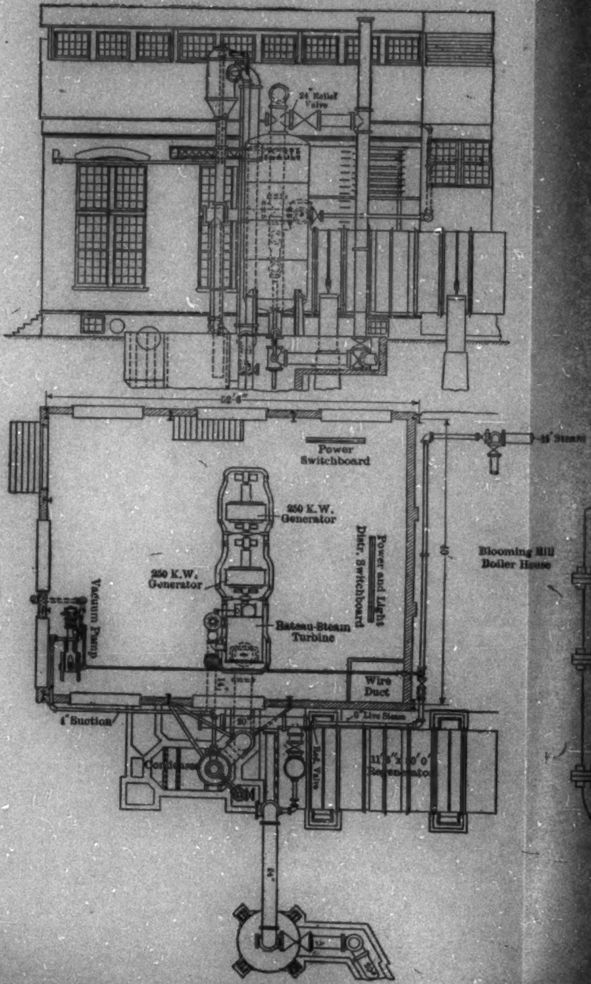
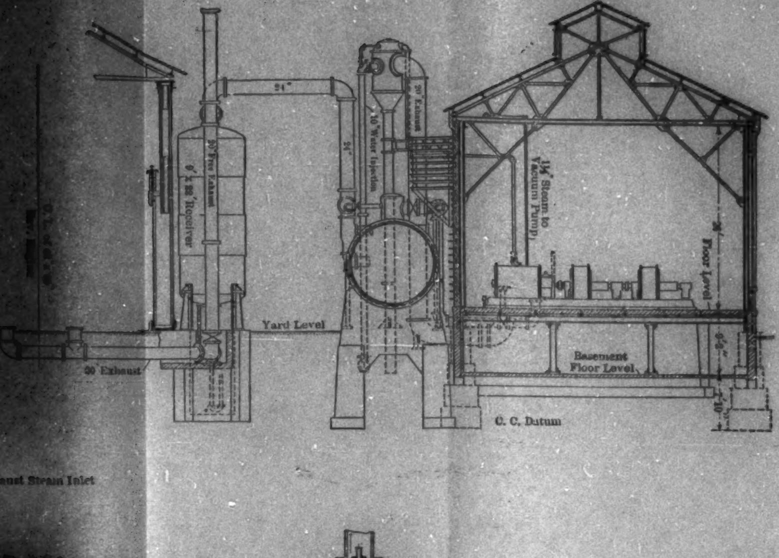

24" Relief Valve
52' 6"
Power Switchboard
12" Steam
250 K.W. Generator
Power and Light Distr. Switchboard
40'
Blooming Mill Boiler House
250 K.W. Generator
Vacuum Pump
Rateau-Steam Turbine
14"
Wire Duct
4" Suction
20"
6" Live Steam
Condenser
Red. Valve
11' 6" x 30' 0" Regenerator
24"

FIG. 2. PLAN AND ELEVATIONS OF LOW-PRESSURE TURBINE INSTALLATIO


24"
20" Free Exhaust
9' x 28' Receiver
10" Water Injection
20" Exhaust
24"
1¼" Steam to Vacuum Pump
Floor Level
Yard Level
30" Exhaust
Basement Floor Level
C. C. Datum
aust Steam Inlet
Check Valve
Section c-d-e-f-g-h
a
To Turbines
Water Gage
C
C
A
10'8"
b
Section a-b
c
C
d
C
B
B
A
A
A
A
g
h

ALLATION, WITH TRANSVERSE AND LONGITUDINAL SECTIONS OF REGENERATOR

atmosphere, will be seen the relief valve which permits the escape of steam to the air during the periods when there is more than the demands on the turbine and regenerator require.

FIG. 3

Accumulator. The accumulator or regenerator is a very interesting piece of apparatus and is virtually the same as the more recent Rateau regenerators built in Europe. It is shown in Fig. 4. Longitudinal and transverse cross-sections of a small regenerator are shown at the right in Fig. 2.

Principle of operation. The accumulator might be called a heat fly-wheel, absorbing or giving up energy in accordance with the requirements. It might also be likened to a storage-battery floating on the line.

When the engine is running, the exhaust steam comes from the engine through the receiver and is delivered to a number of pipes immersed in the water in the regenerator. These pipes or ducts are perforated with a number of small holes, spraying the steam, so to speak, in through the mass of the water in the regenerator. A greater or less proportion of this steam is condensed in passing through the water and gives up heat to the mass of water in the regenerator.

FIG. 4

It is usual to operate the regenerators at about atmospheric pressure. In other words, the steam coming to the regenerator will usually have a temperature of 212° fahr. and will tend to heat the water to just that temperature. If the engine stops and the supply of exhaust steam discontinues, we will see that we have a large mass of water heated to 212° fahr., and if there is a continuous load on the turbine the flow of steam through the turbine to the condenser will tend to make the pressure fall off slightly in the regenerator, and 212° fahr. will then be slightly above the boiling temperature of water at this lower pressure, so that the mass of water begins to give off steam and act like a boiler running at approximately atmospheric pressure. If, now, the engine starts again, steam will be delivered to the accumulator at a temperature slightly above that to which the water has fallen, due to the cooling effect of the evaporation of the steam for supplying the turbine, and the mass of water will again absorb heat from the exhaust steam.

In actual practice it is more convenient to run the regenerator at a pound or two pressure above the atmosphere, as in this case the piping is not under vacuum so that so much care does not have to be exercised to avoid air leaks. However, in certain cases, it is desirable to run below atmospheric pressure. In this way the power of the primary engine may be augmented by letting it operate at a partial vacuum. Plants are actually running with a delivery pressure to the turbines as low as six pounds below atmosphere.

Details of accumulator. The accumulator at South Chicago, being quite a large one, is divided by a diaphragm in the middle into two decks, each deck having a series of flues similar to those shown in the small regenerator of Fig. 2. The steam generated in the lower deck passes up through steam flues into the upper chamber and passes out with the upper steam through the steam dome.

Water trap. There is a small percentage of the steam delivered to the regenerator which is condensed on account of radiation from the surface of the apparatus and this makes an accumulation of excess water in the regenerator, and this is automatically discharged by the float trap seen at the end of the regenerator. In most plants where such apparatus is used, there is more exhaust steam than is actually required for the turbines so that this condensation does not matter as it is only a small percentage anyhow. But in some plants, where the fullest possible amount of steam needs to be saved, the regenerators are lagged.

Water level. Gauge glasses are shown on each deck, and a series of valves and pipes are shown so that the water level in the upper deck can be set to suit that maintained in the lower deck by the float valve.

Reducing valve. If for any reason the primary engine shuts down for a considerable period, the supply of heat stored in the regenerator will become exhausted and the pressure will fall below a workable amount for the turbines. To take care of this condition, there is an automatic reducing valve which will be seen on the piping just above the scaffold. This valve in the present plant is set so that it will open whenever the pressure falls below atmosphere and deliver live steam through the reducing valve to the regenerator whenever the primary engine is shut down for a long enough period to make it necessary.

In this plant the relief valve is set for three pounds above atmosphere; in other words, whenever there is more steam than is necessary to run the turbine and heat the water in the regenerator to a temperature corresponding to its pressure, the excess steam will pass off to the air through the relief valve. On the other hand, if the engine does not give enough steam to supply the needs of the turbine, the reducing valve will open and let in enough live steam to make up the deficiency.

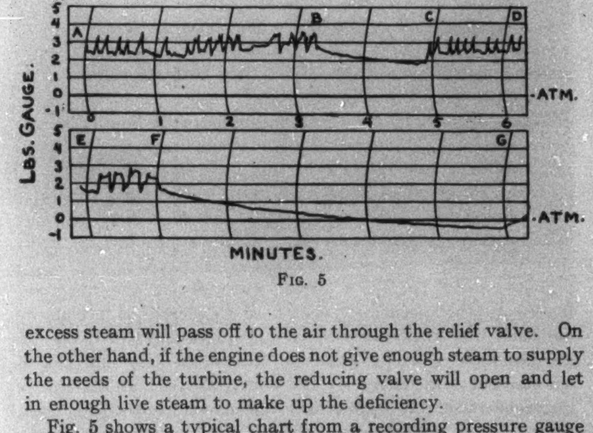


FIG. 5

Fig. 5 shows a typical chart from a recording pressure gauge on a regenerator operating from the exhaust of a roll-train engine. From *A* to *B* the engine is working and the pressure rises and falls as a function of the amount of steam delivered. At *B* the engine stops and the regenerator continues to deliver steam to the turbine so that the pressure begins to fall off down to the point *C*, where the engine begins rolling again. At *F* the engine stops again for a considerable period so that the pressure falls to atmosphere and a little below, until the point *F* is reached, where the pressure has fallen sufficiently to let the automatic reducing valve open and admit live steam, which brings the pressure back up slightly above the atmosphere.

At the Wisconsin Steel Company's plant, during normal operation, the pressure ranges about one or two pounds above atmosphere; when the engine is exhausting heavily it runs up to about three pounds. The lower limit of pressure, when the reducing valve opens, is about atmosphere.

As a matter of fact the regenerator is considerably larger than would be really necessary to regularize the flow of steam to the turbine, as tests show that under the ordinary load conditions the regenerator will keep the turbine running at its average load for about seven minutes after the primary engine shuts down before the reducing valve opens. This would correspond to a period of about five minutes at full load on the turbine.

FIG. 6

Turbine. The turbine is of the well-known Rateau type, similar to those of the same character built in Europe, except that on account of American conditions it was necessary to make the construction heavier and stronger. The exterior of the turbine is shown in Figs. 1 and 6.

Wheels. The revolving wheels and their vanes are shown in Fig. 7. The wheels are turned out of solid steel plate with an cross-section increasing toward the center to give them a large factor of safety.

Buckets. The buckets are made of a special alloy of great mechanical strength and rust-resisting qualities. Each bucket resembles a half of a brass shot-gun cartridge sawed in two. The buckets are held against the rim of the wheel by special rivets which have heads formed to fit the shape of the bucket at the bottom. It will be noted that this is an extremely simple and reliable method of securing each bucket independently of the others. The rivets are figured with a very large factor of safety, and there has never been a case of a rivet giving out in all of the large number of Rateau turbines which are running. The buckets are spaced at the periphery by a spacing or shroud-ring which serves to maintain an accurate spacing and acts as a baffle for improper currents of steam.

FIG. 7

It will be noted that these rings are made in several pieces. This is for the sake of convenience in manufacture and handling and does not materially affect the strength, as will be seen when it is remembered that at these high peripheral speeds a band of this character would have scarcely the requisite strength to hold itself as a hoop. On the other hand, the buckets must be depended upon to hold it as far as centrifugal force is concerned.

It is of interest to note that as the turbine is divided into so many stages, the steam velocities are very low, so that the impinging jets of steam do not wear away the entering edges of the buckets One of these turbines was examined after being in service for five years and it was found that the marks of grinding on the buckets were still visible, showing that the wear was negligible.

FIG. 8

Diaphragms. The Rateau turbines have fixed diaphragms which extend to the shaft between the wheels, forming a cell in which each wheel operates. There are no photographs of the diaphragms of this particular turbine, but they are of the same character as those shown in Fig. 8.

As the turbine is of the impulse type, the pressure is the same on both sides of the wheel and there is no tendency to leakage of steam through the clearance spaces around the periphery. These clearances can therefore be made as large as desired within reason, without having any material effect on the efficiency.

Governor. The governor is of the spring-balanced, fly-ball type, operating in connection with a dash-pot. It is located in the cylindrical casing on the turbine bearing seen in Fig. 6.

Throttle valve. The governor regulates the speed by throttling, the valve being of the double-beat type, located in the vertical cylinder seen in Fig. 1. Of course it will be realized that the steam admission pipe and the throttle valve have to be of abnormally large dimensions on account of the steam being delivered at such a low pressure.

FIG. 9

The governor operates satisfactorily and maintains the speed within the ordinary ranges, either during violent or slow changes of load.

Bearings. The bearings are very simple in construction, as they are practically the same as the ordinary ring-oiled dynamo bearings, except that they have water-jackets to maintain the temperature at the desired value.

The turbine being of the impulse type, there is no end-thrust except that due to slight residual effects, so that only a few thrust-collars are necessary to locate the shaft and these are placed at one end of the governor bearing.

Stuffing-boxes. On low-pressure turbines the stuffing-boxes become a comparatively simple problem; on this turbine they simply consist of a water-seal in chambers bolted to the heads of the turbine.

Dynamos. One of the dynamos is shown in Fig. 6, the armature in Fig. 9, and the fields in Fig. 10.

The design of direct-current dynamos at turbine speeds is the really hard part of the engineering problem connected with such an installation. The turbine itself, being constructed entirely of strong materials, is relatively a simple matter in comparison with the dynamos. The centrifugal force at the periphery of the armature is nearly half a ton per pound of material, and it can be readily understood that the designing of a machine to hold a large number of small insulated coils with an adequate factor of safety, and so placed that they will stay where they are put and not unbalance the machine, is not a problem of the nature of child's play.

Fig. 10

When it was decided to put in this plant we found that direct-current dynamos of the speed and capacity required had not been built in this country and were not obtainable, so it was necessary for us to design the dynamos ourselves. It might also be remarked that although larger direct-current turbine dynamos had been designed in Europe, there were none, as far as we could find out, adapted to the requirements of American steel-mill practice.

In order to make the problem simpler and not run so much risk with abnormally long commutators, it was decided to divide the generating capacity into two direct-current units of 250 kw. each, the pressure being 250 volts.

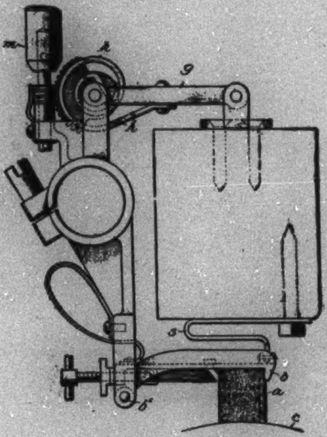


FIG. 10*a*

Armature. The armature resembles an ordinary iron-clad armature, except that everything has to be much stronger and the shaft at the center is very large so as to bring the critical speed well above normal. At the ends of the winding, where there are no teeth to hold the coils against centrifugal force, nickel-steel retaining rings are used, which give a very large factor of safety in spite of the enormous strains. These rings revolving in the fringe of the magnetic field from the pole-pieces would, of course, have a large loss in eddy currents generated in them and would overheat and cause loss in efficiency if something were not done to prevent it.

In Fig. 10, just outside the pole pieces will be seen iron rings which serve as magnetic shields to protect the retaining rings from the leakage flux which would otherwise pass through them. These rings of course increase the magnetic leakage of the fields by a small percentage but this can be allowed for once for all by providing a little extra material in the fields and, on the contrary, the shielding of the retaining rings prevents a loss which would be a continuous one during the operation of the machine.

Commutator. Abnormal peripheral speed limits the size of the commutator diametrically, and the great coefficient of expansion of long commutator bars limits the permissible length in a longitudinal direction. The commutator is therefore divided into two sections, as shown in Fig. 9, to avoid expansion troubles. The segments are held against the great centrifugal force by nickel-steel retaining rings which are shrunk in place and give a large factor of safety to the commutators. The two sections of the commutator are united by tangs resembling those ordinarily used at the inner end of commutators.

Fields. In order to overcome the effects of the very high commutating voltages caused by the large current and high speed, it is necessary to use commutating poles. These are well shown in Fig. 10. The rest of the field structure is of the same general character as ordinary machines. On the right of the field frame in Fig. 10 may be seen half of the turbine shell with the diaphragms removed.

Brush-holders. The brush-holders are one of the difficult features of the problem. I think it may be said that some brush holders are worse than others, but there are no perfect ones.

On these high-speed commutators the energy lost in the brush friction is usually a good many times that of the $I^2 R$ loss, so that it is important to keep the brush tension as low as possible. The other horn of the dilemma is that, unless considerable tension is maintained, it is difficult to keep the commutator absolutely true, and even one-thousandth of an inch eccentricity or a high spot will throw the carbons out of contact and make sparking and other troubles. On these machines the problem is handled in a very interesting manner by a novel type of brush holder, Fig. 10*a*. The carbons are held in a clamp swiveled some distance back of the point of contact, and between the carbon and a lead weight is located quite a stiff spring. The lead weight is held by this spring on one end and the swiveled arm at the outer end. A spiral spring adjusts the tension on the weight. The weight acts like the weight of a seismograph and the brush is therefore acted upon by a strong force tending to bring it back in contact if for any reason it has a tendency to be thrown off the commutator by a high spot or otherwise. On the other hand, the adjusting spring behind the weight enables the maintenance of a low average tension on the brush. In this way the natural period of vibration of the brush and its spring acting against the weight can be made a number of times the frequency of revolution. Care must, however, be taken that the natural period of vibration of the inertia weight, vibrating on the inner and outer springs, shall not be such that resonance will be caused by the frequency of rotation.

Ventilation. These high-speed machines cause a considerable whirring noise on account of high peripheral speed, and for this and other reasons the frames are enclosed with end-bells. On the end of the armature in Fig. 9 will be seen the projecting tips of fan-blades which are mounted on the armature. These draw in air through a passage at one end of the frame and force it through the machine down through a passage at the other end and out through the base. This assures adequate ventilation and makes the machines comparatively quiet in operation.

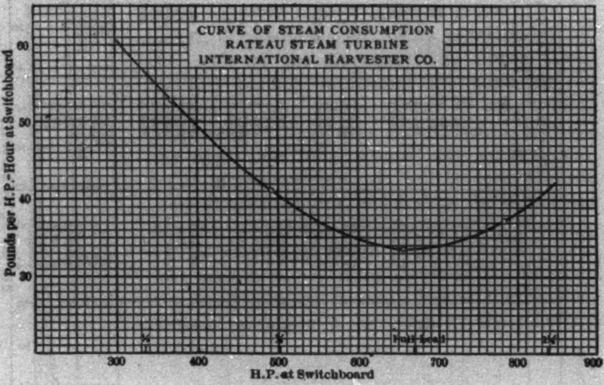
Operation. The general operation of the machines, as regards heating and sparking, is about the same as with ordinary slow-speed dynamos, although it is usual to have slightly higher temperature rises on the high-speed machine, because the losses are concentrated in such small space that it makes the ventilation of abnormal proportions to get down to the limits which are sometimes specified for slow-speed machines.

Regarding the sparking, it may be said that these high-speed machines are quite sensitive to the condition of the commutator surface, as dirt or other causes which tend to keep the brushes out of contact will induce sparking. Sometimes the same cause would not have the same effect on slow-speed machinery. In general it may be said that there is not a great deal of difference in the operation of slow- and high-speed machines.

These machines being equipped with commutating poles, with which the forces to accomplish commutation increase proportionately to the load, have an advantage as compared with ordinary machines in handling temporary overloads, as will be seen from the fact that we have a number of times carried the entire load on one machine for several hours while the other dynamo was running idle.

Condenser. The condenser and air pump are of standard type. It may be remarked that there has been no difficulty in maintaining a good vacuum in normal operation and that the plant is usually run at a vacuum of about 28 inches.

Tests. The tests of the plant have already been referred to. Table I gives the details of the observations. Fig. 11 shows a curve of the steam consumption of the turbine per electrical horse-power at the switchboard. The steam consumption was determined by temporarily putting a Venturi meter in the pipe delivering the condensing water to the condenser and measuring the temperature of the entering and discharged water, in this way using the condenser as a calorimeter to determine the heat rejected from the turbine. It may be well to point out that in order to get suitable temperature ranges and on account of other local conditions obtaining at the time of the test, the vacuums were not as high as the turbine was designed for, so that, although the steam consumption was better than the guarantees, the values given do not represent the actual capabilities of the turbine.



CURVE OF STEAM CONSUMPTION OF TURBINE

FIG. 11

Comparative power of low-pressure turbines. To those not familiar with low-pressure turbines, the query might naturally arise as to how it comes that the low-pressure turbine can get

TABLE I.—RESULTS OF TESTS OF 500-KILOWATT INSTALLATION OF RATEAU TURBINE, STEAM REGENERATOR AND GENERATORS, AT THE SOUTH CHICAGO PLANT OF THE INTERNATIONAL HARVESTER COMPANY

OBSERVED AND DERIVED VALUES	UNIT	TEST NO. 1	TEST NO. 2	TEST NO. 3	TEST NO. 4
Date of trial	1907	Mar. 11	Mar. 11	Mar. 12	Mar. 12
Duration of trial	hours	1.00	2.00	2.00	2.00
CONDENSER					
Average head on Venturi meter	inches	3.48	7.57	14.72	17.77
Average initial temp. of condensing water	° fahr.	38.40	39.30	38.90	39.55
Average final temp. of condensing water	° fahr.	80.00	68.30	61.50	66.55
Average rise of temp. of condensing water	° fahr.	41.60	29.00	22.60	27.00
Average condensing water per min	cu. ft.	151.9	192.8	247.2	295.4
Average condensing water per min	pounds	8,155.0	12,030.0	16,750.0	18,700.0
Average barometer	inches	29.6	29.6	29.2	29.2
REGENERATOR					
Average pressure at turbine, abs.	pounds	16.9	16.6	15.9	15.3
Average temp. of steam at turbine	° fahr.	215.5	217.0	216.3	213.2
Average temp. of air	° fahr.	48.0	48.0	64.0	64.0
Average steam delivered per hour	pounds	19,500.0	20,220.0	22,050.0	29,280.0
TURBINE					
Average pressure above controlling valve	inches	32.9	32.4	30.93	29.75
Average pressure under controlling valve	inches	18.6	19.0	21.47	24.85
Average vacuum at exhaust casing	inches	25.31	26.6	26.95	26.40
Average revolutions of turbine ± 15 per min	r.p.m.	1,540.0	1,540.0	1,500.0	1,500.0
Average brake hp. at turbine shaft	hp.	409.0	544.0	727.0	869.0
GENERATORS					
Average ammeter readings	amperes	1,085.0	1,485.0	2,195.0	2,482.0
Average voltmeter readings	volts	245.2	246.9	233.5	238.3
Average current delivery in kilowatts	kilowatts	266.1	366.7	489.2	591.6
Average efficiency of generators	per cent.	90.2	90.2	90.2	90.2
Average hp. at the switchboard	hp.	369.0	491.0	656.0	784.0
DERIVED RESULTS					
Radiation from piping per min	B.t.u.	2,700.0	2,700.0	810.0	810.0
Heat equivalent of work done per min	B.t.u.	17,490.0	23,250.0	31,100.0	37,300.0
Heat delivered to condensing water per min	B.t.u.	339,100.0	349,000.0	395,100.0	498,100.0
Steam per min. to turbine	pounds	326.0	337.0	367.5	488.0
Steam per kilowatt-hour	pounds	73.3	55.2	45.2	49.5
Steam per hp. at switchboard per hour	pounds	52.8	41.2	33.6	37.3
Steam per brake hp. at turbine per hour	pounds	47.7	37.1	30.7	33.7

so much power out of the exhaust steam. It is quite inconvenient to show this by the ordinary pressure volume diagram, Fig. 12, but this diagram readily shows the difficulty of trying to make a piston engine utilize the expansion of the steam down to the volume realizable with the good vacuums maintained with turbines. The diagram is laid out showing the expansion of 4.21 pounds of steam, which is the average amount of steam used per stroke in the primary engine. The dotted curve shows the volume in cubic feet of this amount of steam expanding without condensation from 140 pounds gauge to atmosphere and from there down to a vacuum of something less than 28 inches, the 28-inch point being considerably off the scale of the diagram. The upper cross-hatched portion represents the adiabatic expansion of the steam down to atmospheric pressure and the lower cross-hatched portion, the expansion from atmosphere adiabatically to 28 inches vacuum. It will be seen that the areas of the diagrams, which show the theoretical power in the steam, are approximately equal.

The theoretical steam consumption of a perfect heat engine working between the limits of the absolute initial pressure P and the absolute exhaust pressure p, is given by the following formula:

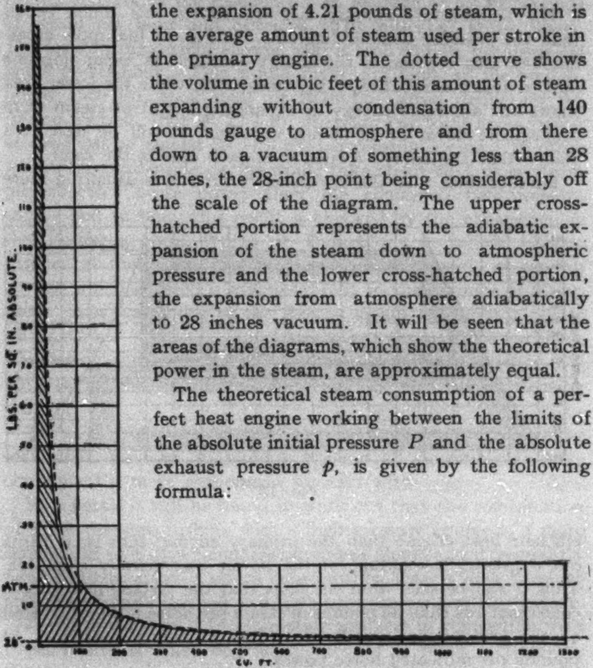


FIG. 12

$$K = 0.85 + \frac{6.95 - 0.92 \log_{10} P}{\log_{10} P - \log_{10} p} = \text{kg. per hp-hr. for metric units}$$

$$\text{or } K = 1.9 + \frac{17.91 - 2.05 \log_{10} P}{\log_{10} P - \log_{10} p} = \text{lb. per hp-hr. English units.}$$

If from this we work back and find the pressure at which a perfect heat engine would have to operate in expanding from boiler pressure down to atmosphere in order to consume the same amount of steam as a perfect engine or turbine working from atmosphere down to 28 inches vacuum, we find that the initial pressure would be about 140 pounds.

The temperature-entropy diagram shows this much better than the pressure-volume diagram. In Fig. 13 the upper cross-hatched area represents the energy available in expanding one unit of steam adiabatically to atmosphere, while the lower area shows the available energy in expanding a unit of steam from atmosphere down to 28 inches vacuum. It will be seen at a glance that the energy available in each case is the same.

Further than this, the low-pressure turbine is usually a more

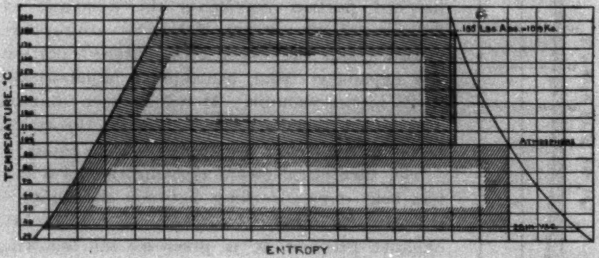


FIG. 13

efficient heat engine than the primary engine; that is, it turns out a greater percentage of the power theoretically available. Thus it will be seen from the tests that the turbine in this case consumed less than 35 pounds of steam per horse power delivered at the switchboard, while the primary engine consumed 54 pounds per indicated horse power.

Condensing engines. The query also arises how the exhaust-steam-turbine plant compares in economy with the primary engine running condensing.

In the first place, it introduces operating difficulties to run reversible engines of this character condensing. Nevertheless, they are being operated this way in a number of instances. We understand that a steam consumption of 25 pounds per indicated h.p.-hour is the best that can be obtained on a compound reversible condensing mill engine and that, when the losses in clearances, condensation, and mechanical efficiency are taken into consideration, the steam consumption per horse power at the shaft would come up to at least 38 pounds.

In comparison we can take the low-pressure turbine plant at the Wisconsin Steel Company as an example. The primary engine delivers to the regenerator an average of 52,400 pounds of steam per hour and develops 1010 indicated horse power. The tests on the turbine showed that it took 33.6 lb. per electrical horse power-hour. This would make available at the switchboard 1560 hp. or a total of 2370 hp., after deducting the engine friction, that is, 22.1 lb. of steam per total horse power at the shaft as against 38 with the condensing engine. In other words, the condensing engine would take about 70% more steam per effective horse power than the combined high-pressure engine and turbine; this result is checked by the experience at the Poensgen Steel Works at Dusseldorf, in which various engines of the plant were connected to a central condensing system which effected a saving of 15% in the amount of steam used. Afterwards one of the Rateau steam regenerator plants was installed, and the exhaust steam put through the turbines. The saving now exceeds 40% as compared with the average of a 15% saving by running all their engines into the condensing system.

The saving in this case is not as great as the example we have just cited, because the engines are not all reversible and are consequently more economical to start with.

In general, it will be found to work out that the combination of a low-pressure turbine with a high-pressure engine is a more economical unit than a condensing engine alone; and it frequently figures out to a lower steam consumption than a high pressure and low-pressure turbine or a high-pressure condensing turbine.

Degree of vacuum. An interesting problem in connection with these plants is what degree of vacuum is most economical. Where the admission pressure to the turbines is so low, the steam consumption is affected to a greater percentage by the vacuum than with high-pressure turbines. In Fig. 14, the Curve T shows the theoretical steam consumption per horse power of a perfect heat engine working between an admission pressure equal to atmosphere and an exhaust pressure of the various inches of vacuum set down as abscissas.

The actual steam consumption per brake horse power would be as indicated in Curve *A*, assuming a constant efficiency of the turbine over the range of the curves. This assumption is not strictly correct but is near enough so over the region of the minimum point which is what we are concerned about. It is seen that both the theoretical and actual consumption decrease very rapidly with a better vacuum, so that, for example, about 25% more power can be obtained from the same amount of steam by running at 28 inches vacuum as compared with 26 inches. On the other hand, it will be found that the horse power required to run the circulating pump and the other auxiliaries increases at a very rapid rate with the higher vacuua, although the power of the air pump decreases slightly.

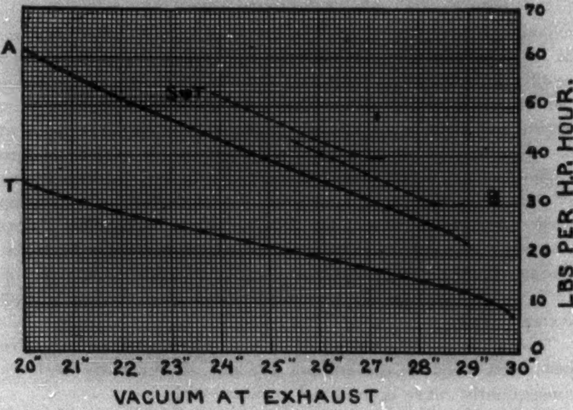


FIG. 14—T = Theoretical consumption of perfect engine per horse power-hour. A = Actual consumption of turbine per brake horse power-hour. B = Actual consumption of turbine per net electrical horse power-hour with barometric condenser after deducting power for auxiliaries. S and T = Consumption per net electrical horse power-hour with surface condenser and cooling tower after deducting power for auxiliaries.

In order to show the effect of the power consumed in the auxiliaries we have taken as an example such a turbine operated in connection with a barometric condenser and assumed that the circulating pump and air pump were motor-driven by current supplied from the dynamo connected with the turbine. This would not ordinarily be the method of arranging such a plant, as the turbine depends on the vacuum as its source of power and it is inconvenient to get the plant started; but such an example offers a clear way for figuring the net output of the plant.

The Curve *B* shows the pounds of steam per net electrical horse power, the power for operating the auxiliaries first having been deducted. This curve is on the basis of circulating water at 70° fahr., (which can be taken as representing average conditions) and the usual commercial forms of condenser auxiliaries. It will be noted that the curve begins to turn up at the higher vacuua instead of turning down as do the theoretical curve and the actual gross consumption curve.

In steel mills there is usually a large water system for supplying the plant, and it is generally thought best to avoid complication and supply the condensing water for the turbine plant directly from the system, without installing a separate circulating pump. The head of the water systems is usually in the neighborhood of four times the head required for the circulating pump. This extra amount of power, although not needed for the turbine plant, has to be considered in determining the most economical vacuum and has the effect of shifting the minimum point to something over half an inch lower vacuum than indicated on Curve *B*.

Where condensing water is not available, a low-pressure turbine plant can be installed in connection with a cooling-tower equipment.

Curves *S* and *T* show the steam consumption per net electrical horse power in a plant equipped with a surface condenser and cooling tower, after deducting the power which would be consumed in motor-driven air, circulating and hot-well pumps, and in the cooling-tower fan. This curve is made out on the basis of 75° temperature of the air and 70% humidity, which are taken as representing average conditions. It will be noted in this case that the most economical vacuum is practically the maximum vacuum obtainable under the conditions.

With the barometric Curve *B*, it will be noted that a higher temperature of the circulating water would move the most economical point to a lower vacuum and vice versa.

These curves are on the basis of machinery of the character under consideration. It would be well to point out that with larger turbines and with alternating-current generators, the efficiency of the generating set and also that of the auxiliaries would be increased so that the points of minimum net consumption would be shifted downwards and slightly towards the right.

These values refer to steam consumption and the real point in most cases is the minimum cost of current. The cost of current in such a plant is almost entirely represented by the interest on the investment and other fixed charges. The intrinsic cost of both the turbine and the condensing equipment increases with the higher degrees of vacuum so that these factors would tend to shift the point of minimum cost of current a slight amount to the left.

Practical results. The general result of the installation of this low-pressure turbine equipment is that it enabled the mill to shut down the two 250 kilowatt engine-driven generators which formerly operated the mill, and for a long time the turbine carried the entire electrical load of the steel mill, operating from the exhaust of the blooming engine and not taking any live steam except during abnormal stoppages of the blooming engine.

Recently they have installed some electrical unloading machinery on their docks. When this machinery is all in operation the load frequently runs up above the ultimate capacity of the turbine and they have to start up one or more of the engines and run in parallel with the turbine.

The attendance and lubrication items for the turbine plant are very small. The turbine is located near the blooming engine, while the other generators are located in the blowing-engine house about a quarter of a mile away. There is but one attendant on duty in the turbine engine room.

At this plant the boilers are supplied principally by gas from the blast furnace, but the supply of gas is quite variable and usually not adequate to give all the steam required, so that more or less coal has to be used. The installation of the turbine, therefore, results in a saving of the coal corresponding to the steam required for operating the dynamo engines. This, as indicated above, is quite a variable quantity but has been variously estimated at from $10,000 to $20,000 per year. In figuring on the installation of the turbine plant, it was estimated that the turbine would effect a considerable saving, even if the supply of gas were generally adequate, as the maintenance of the turbine plant would be considerably less than the corresponding engine and boiler plant, or even a gas-engine plant.

Further, it is well to remember that exhaust steam passing to the atmosphere can be looked upon as the equivalent of a water-power plant and that it usually has the advantage of being near a market for power, besides costing less to develop than a water-power plant would. In other words, the exhaust-steam plant should be able to produce the power cheaper than a corresponding water-power plant.

Cost of power. During three months when the steel plant was running at nearly full capacity. the turbine delivered an average of 188,300 kw-hr. per month, or 51% of the total possible kilowatt-hours if run at its rated load the entire time.

The operating expenses are at the following rates, based on the above output:

Oil, waste, etc.	0.002	cents	per	kilowatt-	hour
Attendance	0.074	"	"	"	"
Maintenance and miscellaneous	0.011	"	"	"	"
Total operating	0 087	"	"	"	"
Fixed charges	0.212	"	"	"	"
Total cost	0.299	"	"	"	"

The fixed charges are figured on the basis of a cost of $80 per kilowatt. This figure would, of course, vary considerably with the conditions, but it can be taken as an average for moderate-size plants. Interest, depreciation etc. are allowed for at 12%. Nothing is allowed for superintendence, as no additional force is required for this item.

The cost being made up so largely of fixed charges, it varies very markedly with the load-factor. In fact, if the plant is run 24 hours a day, the lubrication, attendance, and maintenance are only affected to a slight extent by the amount of load, so that they have almost the same effect as a fixed charge. Of course if the plant were run only during the day shift the operating expenses would go down

The effect of the load-factor on the cost is seen in Fig 15, the load-factor here being taken as the ratio of the actual output, divided by the output if run the entire time at rated load

Metallurgical operations. It will be noted that the cost of power at the larger load-factors is extremely low and would be even more so in a larger plant where the first costs and the other costs would go down considerably

If the exhaust steam turbine plant were used for electric smelting or similar purposes, it is probable that the load-factor could be kept up over 80%, which we see from the curve, gives a cost of 0.19 of a cent per kilowatt-hour.

It might be remarked that the electric smelting processes take, on a very crude average, one kilowatt-hour per pound of

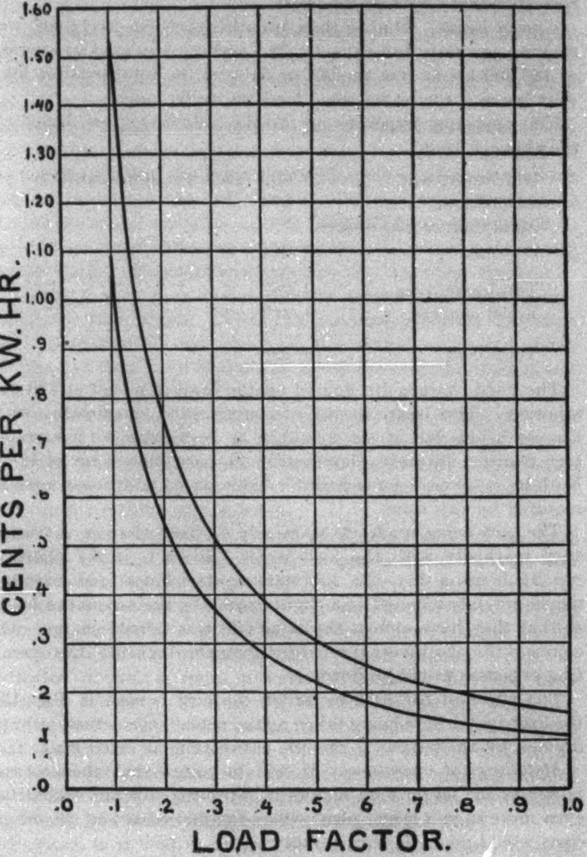


Fig. 15

metal produced. It will therefore be seen that such plants offer a good opportunity for doing certain kinds of metallurgical or similar work.

In the foregoing no value has been assigned to the exhaust steam. In most places where such exhaust steam occurs, there is not a good opportunity to utilize any considerable portion of it in any other ways, so that it would otherwise be a waste product. In case of selling power, it will be seen that either the steam itself or the current produced could be profitably sold to outside parties.

Under these conditions the question of the continuousness of the power would arise. Of course when the primary engine shuts down for more than a few minutes, there is a tendency for the boilers to blow off at the safety valve, so that for short periods it does not mean any more fuel, even if the primary engine is stopped. If the primary engine is stopped altogether, the boilers stand ready to furnish the steam to the turbine and the latter would consume approximately the same amount of steam as non-condensing engines would. If this condition of running with live steam were one that would occur for a considerable time, it would be advisable to install a mixed high-pressure and low-pressure turbine; that is, one which would have a high-pressure section which is automatically fed with high-pressure steam whenever this becomes the normal source of steam. Such plants as this are already operating in a number of places where the primary engine runs only during a day shift and it is necessary to have the electric power day and night.

Field of usefulness. The foregoing remarks apply more particularly to the conditions in a steel plant, but similar conditions occur with large mining hoists; of course any other source of exhaust steam, whether intermittent or not, can be utilized in similar fashion. It has been already pointed out that a great saving can be effected in connection with continuous-running engines, and that such a system can be used to increase the power of such engines and that, even when run condensing, the power and total economy can sometimes be increased by combining a low-pressure turbine and engine.

DISCUSSION ON "AN EXHAUST STEAM TURBINE PLANT", AT NEW YORK, DECEMBER 13, 1907.

Francis Hodgkinson: The combination of a turbine utilizing steam at atmospheric pressure in conjunction with a reciprocating engine is by no means new, although the one described is probably the first installation in this country of such apparatus in conjunction with a Rateau heat accumulator. However, leaving out any value there may be in the heat accumulator, there is no doubt that power plants now operating non-condensing and requiring increased capacity would do well to obtain it by low-pressure turbines so long as means of condensing the exhaust steam are available within reasonable expense. There are many power plants employing high-grade compound reciprocating condensing engines where the total expansion is such that the engines have a higher efficiency ratio when operating non-condensing (efficiency ratio, not steam economy), than when operating condensing. In making this statement I have more in mind high-grade engines for modern power plants, than such prime movers as blooming-mill engines where the expansion when exhausting even to atmosphere is somewhat incomplete. The power-plant engineer, therefore, should not expect to make the large percentages of increase in economy that the author cites in the case of the Wisconsin Steel Company, and the Poensgen steel works, at Dusseldorff.

In the case of the Dusseldorff installation, presumably most of the engines were simple engines, if compounded at all, it was probably with low cylinder ratios. Hence, merely turning the exhaust from these into a condenser would not make material difference in the steam consumption; but exhausting them instead through a low-pressure turbine, and thence into the condenser would, if the power from the turbine be made use of, cut the steam consumption per unit of power to about one-half what it was before.

Low-pressure turbines are not only applicable for working in conjunction with non-condensing reciprocating engines in which the steam expansion is incomplete, but just as much in conjunction with engines designed for operating condensing. A low-pressure turbine can, furthermore, just as well be designed to operate at less than atmospheric initial pressure, should the performance of any given high expansion ratio reciprocating engine show a higher efficiency ratio when exhausting at some pressure less than atmosphere.

One obvious reason for the beneficial results of low-pressure turbines is due to the large temperature drops as low steam pressures are reached, which in the low-pressure cylinder of the reciprocating engine are harmful because of condensation and re-evaporation as the cycles are reversed. This objectionable condition does not exist in the low-pressure turbine.

As an instance of the advantage of low pressure turbines, assume a compound reciprocating engine of cylinder ratios of 3.5 : 1, say of diameters 28 in. and 52 in.; this with 150 lb. initial pressure may be assumed of 1000 kw. economical capacity when running condensing and having a steam consumption of about 22 lb. per kilowatt-hour. This engine, if operated non-condensing, could have valve gears adjusted to develop 1700 i.h.p. when it would consume about 20 lb. of steam per i.h.p. per hour. This gives 30,600 lb. steam available for the turbine, allowing 10 per cent. of moisture in the exhaust of the reciprocating engine. The total amount of steam passing the reciprocating engine, however, being 34,000 lb. 30,600 lb. would develop not less than 1,073 brake horse power in the turbine. Allowing

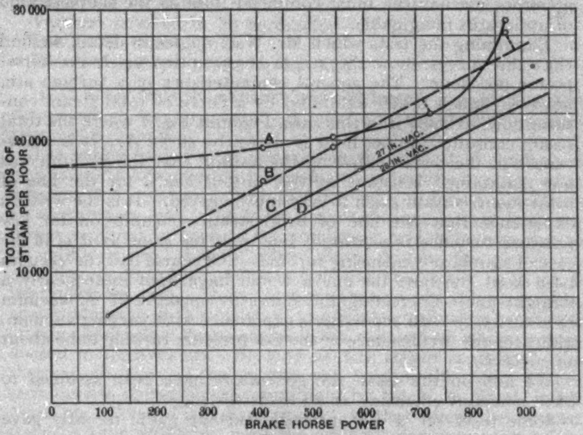


FIG. 1

94 per cent. for the mechanical efficiency of the reciprocating engine, the combined horse power developed would be 2673 brake horse power and the steam consumption of the two units 12.7 lb. per brake horse power-hour, or 18 lb. per kilowatt-hour, which is a remarkable performance for engines of such capacities operating without superheat. Compared with the performance of the reciprocating engine running condensing, this gives 75 per cent. increase of power and 18 per cent. saving of steam.

One very nice feature of low pressure turbines when used in conjunction with reciprocating units where the electric energy from each may be connected to the same bus-bars, is that the turbine need have no governor other than a safety stop. In the case of alternating-current generators, they are locked together, electrically, the steam turbine doing all the work that it can within its pressure limits and in the event of the load becoming light, the available steam will be proportionately reduced by the governors on the reciprocating engines. In the case of direct current units the generators may be shunt wound, which makes them self-regulating in a precisely similar manner, inasmuch as the voltage varies nearly directly as the speed, and the load will divide itself properly between the reciprocating unit and the turbine.

A low-pressure turbine built for such purposes naturally contains very few rows of blades as compared with ordinary turbines, the volume of steam being large permitting generous blade proportions and having neither regulating valve nor governor mechanism, must commend itself as the simplest kind of apparatus imaginable.

Examining the tests which Mr. Wait quotes in detail, we find that the curves show the steam consumption per brake-horsepower per hour. The general characteristics of a turbine are, however, much better exhibited by a curve of total steam consumption; to show it in this case, I submit Fig. 1 where the total steam consumption per hour is shown by curve *A*. It is unfortunate in the tests quoted by the author, that the vacuum was not maintained constant at the various loads, for the line of total steam consumption is very much curved. It is the writer's experience that the line of total steam consumption for low pressure turbines is a straight line, just the same as it is in the case of standard condensing turbines. Of course had the vacuum been kept constant the curve would have been more nearly a straight line. Correcting this curve to constant 27 in. vacuum in accordance with the writer's experience with varying vacuum, indicates the performance of the low pressure turbine to be about as curve *B*.

We note in the tests, the generators have been assumed to have constant efficiency at all loads tested.

Some tests on a low pressure turbine made recently gave the following results:

Steam pressure pounds per square inch absolute. Dry and saturated steam	Vacuum in exhaust inches mercury, referred to 30 in. barometer	Load in brake h.p.	Total steam per hour	Steam consumption brake h.p. hour
17.4	25.98	920	25670	27.9
12.4	25.99	472	17487	37.1
11.8	26.97	592	17720	29.9
7.7	27.03	321	11980	37.3
5.2	26.98	102	6570	64.4
11.6	27.8	586	16400	28.00
8.7	28.00	458	13920	30.4
6.1	27.90	234	9036	38.6
4.5	27.90	114	6248	54.8

It will be observed from the above table that various loads were carried at constant vacuum, and sets of tests were also made with different vacuums. In these particular tests high-pressure steam was used, but care was taken to inject enough water to reduce the superheat at the inlet pressure to zero The results of two of these sets of tests: namely, at 27 in. and 28 in. vacuums, are shown in Fig. 1 and from these were deduced the corrections to constant vacuum which I have applied to the author's test.

Another turbine built to operate in connection with high-pressure reciprocating engines gave the following result in shop test:

Initial steam pressure, 15 lb. absolute.
Superheat 40° fahr.
Vacuum referred to 30 barometer—23 in.
Load 1500 brake h.p.
Pounds steam per brake h.p-hr. 35.5.

In all these tests the exhaust was condensed in a surface condenser, which assures accuracy in measuring the steam consumption.

The author makes some remarks on the subject of condensers as applied to low-pressure turbines and endeavors to show what vacuum it is most expedient to carry with different conditions of temperature, etc. He draws his conclusions largely from the power required to operate the condenser, which he assumes to be motor-driven. Except when motor-driven, the power required to operate the condenser does not necessarily have much bearing on the case. There are many reasons why it is preferable, as is customary in this country, to operate condensers by means of non-condensing steam engines, the exhaust of which is condensed in feed-heaters. So long as this steam is utilized, the thermal efficiency of the engines will be something like 87 per cent., as has already been pointed out by Mr. H. G. Stott, in his paper on " Power Plant Economics ", so that where the exhaust steam is thus profitably used the amount of power required to operate the condenser is almost immaterial.

It is unfortunate we are not given more information regarding the performance of the heat accumulator, especially as to how much energy it is capable of storing up and giving out. We calculate from the published description that the regenerator has normally 100,000 lb. of water in it. Mr. Wait says it blows to atmosphere at three pounds gauge pressure, 222° fahr. The reducing valve admits live steam at atmospheric pressure 212° fahr. and that the regenerator normally works between these limits. This gives a temperature range of 10° and Mr. Wait says the turbine will carry load for 7 min. without exhaust steam from the reciprocating engine or the admission of live steam. With this range of temperature, the regenerator will take up and give out 1,000,000 B.t.u. the equivalent of

$$\frac{1,000,000}{961.8^*} = 1040 \text{ lb. of steam.}$$

which will run the engine $\frac{1040 \times 60}{27,000} = 2.31$ min.

27,000 being the assumed steam consumption of the turbine. The other 4.69 min. to make up the 7 min. quoted by Mr. Wait, requiring 2110 lb. of steam would be accounted for if there were 280,000 cu. ft. contents in the receiver, steam space of regenerator, piping, etc.

I should think that better results would be obtained from the regenerator by having the turbine large enough to carry its load without the reducing valve having to admit live steam until the temperature has fallen to, say 180°, when something like three times the heat will be absorbed and given out by the regenerator.

J. R. Bibbins: It is interesting to note that the steam velocities are reduced to so a low point by subdivision of the expansion into a large number of stages, that no appreciable erosion has resulted from moisture in the steam. This, of course, is an extremely desirable feature, particularly for a low-pressure turbine in which the maximum amount of suspended moisture is found, as compared with the high-pressure element of a complete machine. In a standard complete expansion turbine operating on superheated steam, the so-called "dew point" where moisture begins to appear, may not occur until a considerable number of expansion stages have been transversed by the steam; so that while part of the high-pressure section of the turbine runs in superheated steam, the steam traversing the low-pressure section increases in moisture more or less approximating the adiabatic law. For instance, assuming ideal adiabatic expansion between the limits of 165 lb. absolute and 28 in. vacuum, the moisture in suspension would gradually increase to about 23 per cent. In practice, however, internal heat interchanges, considerably reduces this moisture, perhaps as much as 50 per cent. Thus, the low-pressure turbine is obliged to work with steam containing large amounts of moisture, and the necessity of low steam velocities is apparent, not only as affecting depreciation, but also efficiency.

In actual installations of low-pressure turbines, it is possible to trap out some of the suspended moisture in the engine exhaust and deliver steam approaching a dry saturated condition to the turbine. Here the average moisture encountered in the low-pressure turbine would evidently be lower than in the corresponding expansion stages of a complete expansion turbine operating on saturated steam. Or a heating chamber might be introduced between engine and turbine for the purpose of completely drying, or slightly superheating, the low-pressure steam. Owing to the low temperatures at which this could be accomplished, it is possible that some of the waste products of a factory or power station might be utilized to good advantage—hot gases from heating furnaces, possibly boiler-flue gases, in cases where underground flues were employed leading to the chimney.

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* 961.8 is taken as the mean heat of evaporation between steam at 212° and 222°.

Although it is true that the impulse or velocity type of turbine may have as large peripheral clearances as desired around the bucket-wheels, it must not be inferred that correspondingly small clearances at the shaft are not necessary to prevent the leakage of steam between the various pressure stages, also that the side clearances between the buckets and nozzles must be small, while in the reaction or pressure type turbine the side or axial clearances may be made as large as desired without affecting the efficiency, owing to the fact that the entire steam space or annulus surrounding the rotor is always filled with working steam.

As low-pressure turbines are usually started under vacuum, provision must be made for flooding the water packing until the turbine picks up its speed sufficiently to provide its own water-seal. This, of course, is easily accomplished from the ordinary water service pressure; otherwise, the vacuum would be seriously interfered with by the air leakage.

A paper presented at the 223d Meeting of the American Institute of Electrical Engineers, New York, December 13, 1907.

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A NEW CO_2 RECORDER

BY C. O. MAILLOUX

In the very valuable paper on "Power Plant Economics," presented before this Institute, Jan. 26, 1906, by Mr. H. G. Stott, (Trans. Vol. XXV, pp. 1-27), attention was called to the utility of records of the percentage of CO_2 (carbonic dioxide) present in the flue gases of a boiler plant, as a means of determining and of preventing those fuel losses which might be termed "avoidable".

Mr. Stott's paper contains curves and data which show quite conclusively that there is an important and close relation between fuel-economy and the percentage of CO_2 contained in the flue-gases. In analyzing the average loss incidental to the conversion of the energy of a pound of coal into electrical energy, he finds, in the case of one of the most efficient plants in existence, that the "loss to the stack" amounts to 22.7 per cent. It is well known that in the majority of cases this loss exceeds 30 per cent. Mr. Stott refers to a case where the loss was approximately 40 per cent. of the thermal value of the coal. The utility of CO_2 records, as a means of locating the "leak", in a case of this kind, is made apparent by the following statement, quoted from Mr. Stott's paper:

"Fig. 2 shows what improvement may easily be obtained by watching the CO_2 records, and indicates a saving of about 19 per cent. over the previous case."

In the time which has elapsed since the reading of Mr. Stott's paper, the importance of "watching the CO_2" has been demonstrated in hundreds of cases, here and abroad, in a manner which no longer leaves room for doubt. As an example of a recent appreciation of the utility of complete knowledge of the CO_2, in flue-gases, the following emphatic statement is of interest:

"It cannot be too strongly impressed upon the power-plant owner that CO_2 is the factor upon which depends his very existence under any circumstances of real competition".

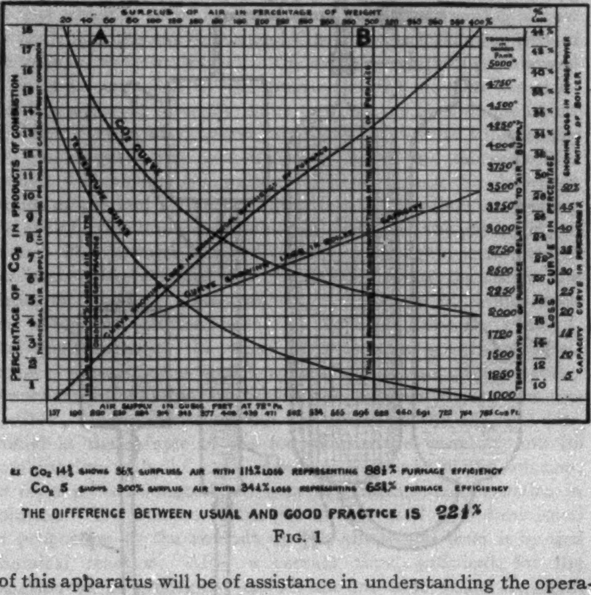
This statement is made by Mr. W. D. Ennis, a leading authority on fuel-economy. It is quoted from the *Engineering Magazine* of June, 1907, containing the first of a series of articles by him, on "Efficiency in Fuel Burning", in which the entire subject is treated exhaustively. Many other citations to the same effect could be made. These will suffice to demonstrate the desirability of CO_2 records, and of satisfactory apparatus for obtaining such records, in the boiler room. Incidentally, they call attention to two sources of reliable information regarding the scientific (chemical and physical) principles on which the value of the percentage of CO_2 as a criterion of the efficiency of a steam boiler depends.

It is not within the scope of this paper to enter into a detailed discussion of these principles. For our purpose, a sufficient idea of these principles and of their consequences may be obtained from the graphical "summary" or "resumé" of them indicated by the curves in Fig. 1, which were prepared and placed at the disposal of the Institute by Mr. H. J. Westover, the inventor of the present CO_2 recorder. The ordinate values of the different curves, at the points where these curves intersect the vertical line *A*, when interpreted by reference to the proper scales of values, represent the condition of "good" practice. The vertical line *B* marks, in the same way, the conditions of "bad" practice.

The average working conditions and the economic results attained, in the majority of steam plants, are such as would correspond to a characteristic vertical line located somewhere between the vertical lines *A* and *B*—as a rule, nearer *B* than *A*. In a few "glorious" examples, that characteristic line is at the *left* of the line *A*. In many "horrible" examples it is at the *right* of the line *B*.

We see, at a glance, in Fig. 1, that high efficiency corresponds to high percentage of CO_2, in the flue-gases. We also see that the falling off in percentage of CO_2 and in the fuel efficiency, is due primarily to *excess* of air. From this, it becomes obvious that the percentage of CO_2 present in the flue-gases, being influenced directly and solely by the conditions of combustion of the fuel, can serve as a criterion of the performance and efficiency of the boiler plant, and as a means of detecting defects and of suggesting improvements in its operation.

This has been known more or less generally, for a long time, and it has been the practice of many experts to make chemical analyses of the flue-gases in connection with boiler tests. The oldest and most widely known form of apparatus used for this purpose is that of Orsat. Since a knowledge of the principle



Ex. CO_2 14½ shows 56% surpluss air with 11½% loss representing 88½% furnace efficiency
CO_2 5 shows 300% surplus air with 34½% loss representing 65½% furnace efficiency

THE DIFFERENCE BETWEEN USUAL AND GOOD PRACTICE IS 22½%

FIG. 1

of this apparatus will be of assistance in understanding the operation of a new form of CO_2 recorder to be herein described, a brief reference to it will be made.

The Orsat apparatus is represented diagrammatically in Fig. 2. The movable vessel *E*, of glass, containing water, is connected by a flexible (rubber) tube, *F*, with a stationary vessel *G D*, of glass, of the general form shown, having graduations at the upper part of the tubular portion *G*, and connecting, by a small tube, *C*, with a three-way coupling in which are valves or stop-cocks, *A*, *L*, and *M*. The cock *L* controls a connection leading to a receiving vessel *H*, filled with small glass tubes, and connected, at the bottom, by a bent tube, with a supplemental receiver, *I*, which is open to the atmosphere, at the top. The

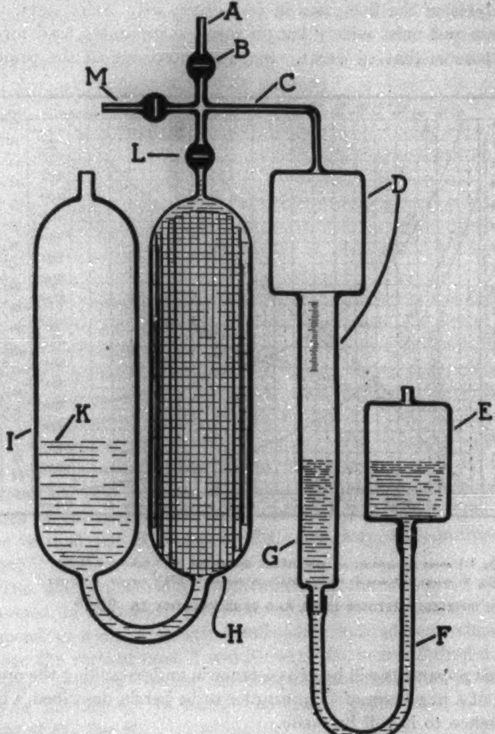


Fig. 2

liquid put in the vessels *H* and *I* depends on the particular gas which is to be analyzed. When the apparatus is to be used for determining the percentage (by volume) of CO_2 in flue-gases, the liquid put in these vessels consists of a solution of caustic soda, or caustic potash. The process of making an analysis comprises various manipulations which must be made in proper order, with a certain care, each requiring a certain time. The cocks *M* and *L* being both closed, the cock *B* is opened, leaving a free passage from the receiver *D* to the atmosphere. The movable vessel *E* is then raised, causing the level of the liquid to rise in the vessel *G* and the liquid to fill the portion *D* as far as the small tube *C*. The cock *B* is then closed, and the cock *M*, controlling the connection with the supply of gas, is opened, allowing the gas which is to be analyzed to enter. The vessel *E* is now lowered; and the gas enters and fills the vessel *D* and a part of the vessel *G* as far as desired. The exact quantity of gas allowed to enter is controlled by the position of the movable vessel *E*, which is adjusted carefully, so as to bring the level of the liquid in *G* to a certain mark, corresponding to a definite volume, say 100 c.c. of gas. The cock *M* is then closed and the cock *L* is opened. The vessel *H* is normally left filled with the absorbent liquid, at the end of the preceding test. Therefore, on opening the cock *L*, this liquid begins to fall, in *H*, and the gas begins to enter. The movable vessel *E* is now raised again until the gas has been entirely forced out of the vessel *D* by the rise of the liquid in *G* and *D*. The gas enters the vessel *H*, forcing down the absorbent solution, which is displaced into the vessel *I*. The glass tubes in the vessel *H* present a greatly increased surface, wet with the caustic soda or potash solution, whereby the chemical reaction on which the analysis depends is expedited. This reaction is the absorption of the CO_2 gas contained in the sample of gas forced into the vessel *H*, and its combination with the soda or potash contained in the solution, to form a " carbonate ", of soda or potash, which remains in solution. The volume of the gas in the vessel *H* is diminished in proportion to the amount of CO_2 abstracted from it by this chemical reaction. After a certain time, sufficient for the reaction to be practically ended, the movable vessel *E*, which was held at its upward position during the time allowed for the reaction to take place, is lowered, causing the residue of gas to return into the vessel *D*. The vessel *E* is lowered until the liquid in *H* rises and fills the vessel to the top as far as the cock *L*. If the sample of gas contained no CO_2, it will not have been reduced in volume when it returns into the vessel *D*; and the level of the liquid in this vessel will be at the same mark as it was before the gas was sent into the vessel *H*. If the gas contained CO_2, the volume returned from H to D will be smaller than it was before; consequently, when the "residue" has all passed out of H, the liquid in G will stand at a higher mark than before. Suppose, for example, that the initial volume was 100 c.c. and that the residual volume is found to be 92.5 c.c. Then, the percentage (by volume) lost, in passing through the vessel H, was $= 100 - 92.5 = 7.5$ per cent. Since the loss in volume was due to the absorption of CO_2 only, it follows that this sample of gas contained 7.5 per cent. of CO_2. If the residue is not to be subjected to further analysis, the cock B is opened and the gas is forced out at A, by raising the movable vessel E and filling the vessel D, as before. If it be desired to analyze the residue for some other gas, say oxygen, for example, the pipe A is connected with another vessel similar to the vessel H and containing a chemical reagent which can absorb the gas whose percentage is to be determined. The reagent used for the oxygen analysis is pyrogallic acid dissolved in a solution of caustic potash. The operation is conducted in substantially the same manner as for the estimation of the percentage of CO_2. The residue of gas is returned to the vessel D, its volume is measured, and the loss of volume, if any, is noted, as before. Suppose the volume be now found = 90 c.c. Then the percentage of oxygen which was present in the gas was $92.5 - 90 = 2.5$ per cent. A third analysis may serve to determine the percentage of CO (carbon monoxide), present in the sample. The reagent then used is cuprous chloride, dissolved in hydrochloric acid. The residue left after this determination will be substantially all nitrogen. From the data thus obtained it is possible to determine the percentage of CO_2, O, CO, N, and of air, contained in the flue gas.

Various other forms of apparatus for gas analysis have been devised and are known under different names, such as the apparatus of Wilson, Elliott, Hempel, etc.

(Further details and also some bibliographical references concerning methods of flue-gas analysis will be found in Carpenter's "Experimental Engineering", Chapter XIV.)

These different forms of apparatus are all, in reality, transplantations from the chemical laboratory, modified and simplified as far as practicable, to render them more transportable, and more suitable generally, for the purposes of flue-gas analysis. They are only intended and, obviously, would only be suitable, for the purpose of making a few analyses at a time, under "laboratory" conditions.

In order that the results of flue-gas analysis may be of service in the operation of a steam boiler plant, it is necessary that these analyses should be obtained under conditions which satisfy certain indispensable "practical" requirements, including the following: 1st, the apparatus should work automatically, without more care and attention than any ordinary apparatus of "mechanical" character;

2d, it should give results (analyses) quickly and regularly;

3d, it should give a visual indication and record of all the results.

For the purposes of information and guidance, in regard to the economic operation of an average boiler plant, it is not necessary that analyses should be made of *all* the constituents of the flue-gases. This would require a too much complicated apparatus, and would lengthen too much the time required for each operation. Practically, the determination of the percentage of CO_2 is all that is required.

Various forms of automatic CO_2 recorders, which meet the above requirements more or less satisfactorily, have been devised and have been put into commercial use, during the last three or four years. Although some of these CO_2 recorders have done and are still doing good work in many cases, their applicability and usefulness in other cases have been restricted by the presence of conditions and the absence of features which rendered modifications and improvements very desirable.

The present CO_2 recorder, which has recently been perfected, is the result of careful analysis of all the requirements and of a critical study of the weak points and drawbacks of all the preceding forms of CO_2 recorder. The new features especially desirable from the point of view of the boiler room manager are: 1st, to make the apparatus more "rugged" mechanically, and, consequently, less liable to break down or derangement from mechanical causes; 2d, to do away with the necessity for any technical knowledge or skill; and to reduce to a minimum the amount of ordinary care and attention, necessary to keep the outfit in good operative condition; 3d, to reduce to a minimum the time required for each analysis and to increase as much as possible the total number of analyses obtainable per hour; 4th, to increase the accuracy of the apparatus by eliminating all errors due to variations of the temperature, of chemical composition of the reagent, or of barometrical pressure; also all errors due to frictional resistance in the recording mechanism;

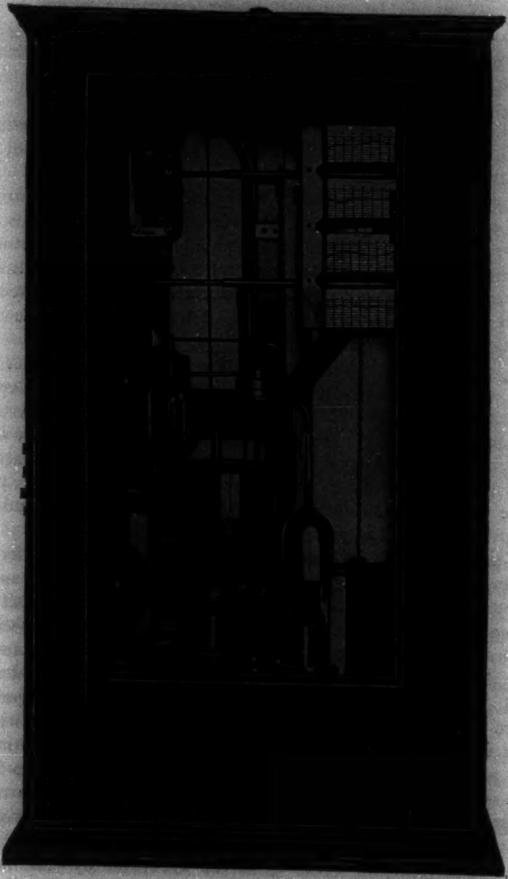


FIG. 3

5th, to make the same apparatus give CO_2 records for several boilers, thereby reducing the cost of equipment per boiler.

Fig. 3 shows this CO_2 recorder arranged to give CO_2 records for a battery of four boilers. Fig. 4 is a theoretical diagram of the apparatus.

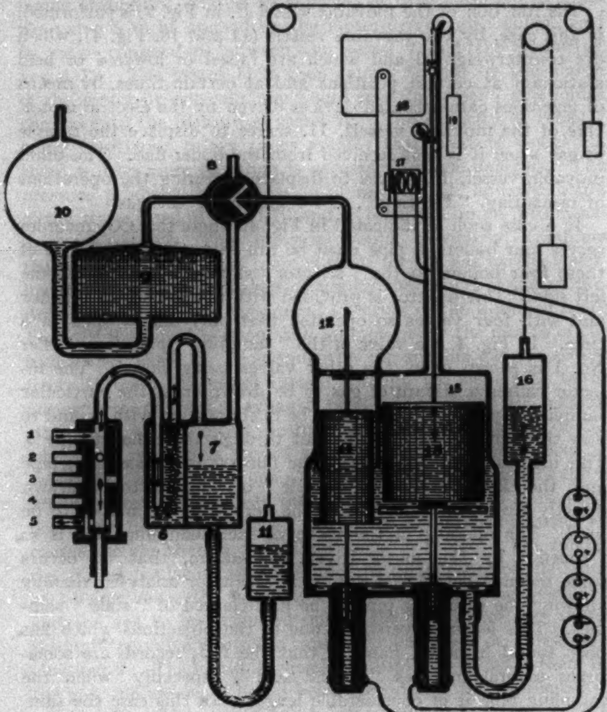


FIG. 4

Each complete analysis of a sample of gas comprises, in this case, a succession of steps or a cycle of operations very similar to those described in connection with the Orast apparatus. All the manipulations are made automatically the work incidental thereto being done by a small constant-speed electric motor partly visible at the lower left hand portion in Fig. 3. This motor drives, through suitable speed-reducing gearing, the mechanism by which all necessary movements of valves, liquids, recording devices, etc., are effected and controlled, in systematic manner.

The function of the movable vessel *E*, in Fig. 2, is performed, in this case, by two movable vessels (11 and 16, Fig. 4), which are counterweighted and which are raised or lowered or held stationary at certain positions and at certain times, by means of ingenious cam-actuated devices driven by the electric motor. One of the movable vessels, 11, serves to displace the sample of gas when it is first received from the boiler-flue. The other movable vessel, 16, serves to displace it during the operations of measuring, " treating ", and remeasuring the gas.

In a case such as indicated in Fig. 4, where the CO_2 recorder serves four boilers, a pipe must be run from the flue of each of these four boilers to the " selector " shown in Fig. 4, at the left side. This selector is provided with a small steam injector and with four valves so operated that only one is open at a time. In Fig. 4, the valve of the " sampling " pipe from boiler No. 1 is shown open, the other valves being closed. The injector causes a stream of gas to be drawn from the particular sampling pipe which happens to be in connection with it, and to flow through the selector and out through the exhaust pipe 5. This insures a rapid motion of the flue-gas in the sampling pipe and, therefore, enables a " sample " of flue gas to be drawn directly from the boiler flue at the very time when it is to be used. The opening of the valve of each sampling pipe is so " timed " by the motor-driven mechanism, that it occurs some seconds before the sample is taken for analysis, thereby allowing the sampling pipe to be first cleared of " stale " samples. This feature overcomes one of the objections which has been found hitherto, namely, that the CO_2 records are sometimes several minutes " behind time ", especially when the sampling pipe is of considerable length. In this case the sample is taken into the recorder, through the receiving vessel, 7. Before the sampling pipe is " cleared ", the movable vessel 11 is raised to its highest position by the action of the cam, thus causing the liquid to fill the vessel 7 and empty it of all gas. When a new sample is to be taken, the vessel 11 descends, causing the liquid in vessel 7 to lower, and consequently, causing a certain volume of gas to be " aspirated " from the selector into vessel 7. This gas is prevented from leaving the vessel 7 by the sealing action of the liquid in the pipe connecting with the selector.

When the vessel 11 has reached its lowest position, it remains stationary, during an interval of time sufficient to allow the valve 8 to be opened by the motor-driven mechanism, and to make connection between the vessel 7 and the measuring vessel 12. The vessel 11 is then caused to rise by the action of the motor-driven cam; the liquid rises in vessel 7 and forces the gas into the measuring vessel 12. The capacity of vessel 7 being from four to six times greater than that of vessel 12, there will be more gas than is necessary for one analysis. The pressure produced by the rising of receiver 11, and the rising of the water level in vessel 7, tend to force the liquid into measuring vessel 12. This pressure would, obviously, compress the gas, were it not that room is made for the gas by the lowering of vessel 16 (which then occurs by the action of the motor-driven cam), and the consequent lowering of the liquid in space 14, until the liquid is about half an inch below the mouth of the measuring vessel 12. Consequently, the surplus gas can escape freely through the vessel 13 and through the vent pipe to the atmosphere or to an exhaust pipe. The vessel 16 remains stationary at its lowest position for a brief interval, during which the valve 8 is moved so as to close the connection between 12 and 7 and open the connection between 12 and 9. The displacement vessel 16 then begins to rise. The consequent rise of the liquid and of the " float " 14, in measuring vessel 12, causes the gas therein to be imprisoned or sealed. The further rise of the displacing vessel 16 and the further rise of the liquid at 14 now cause the liquid to rise in the measuring vessel 12, and the gas to be displaced out of the said measuring vessel, through the valve 8 into the caustic potash vessel or " treating " chamber 9. The liquid in vessel 9 is displaced to make room for the gas, the excess of liquid being forced into the supplemental receiver 10. The chamber 9, being of relatively large diameter and filled with iron-wire netting, presents, as the level of the liquid in it is lowered, a very finely subdivided chemical surface which is wet with the chemical reagent (caustic soda or caustic potash). The amount of surface exposed is approximately 40 times greater than the area of cross-section of the vessel 9; consequently, the rapidity of the absorption of the CO_2 is greatly increased. The presence of this iron netting has the further advantage of stirring and mixing up the solution when it rises again in the vessel 9, which happens when the vessel 16, after having reached the upper end of its "excursion" and having remained there a certain length of time, now descends, allowing the level of the liquid to fall in vessel 14, thereby reducing the pressure exerted on the gas in the vessel 9, causing the unabsorbed gas or "residue" to return from the vessel 9, through the vessel 8, into the measuring vessel 12. This return process is assisted by the simultaneous fall of the level of liquid in the compensating vessel 10, and its rise in vessel 9. It will thus be seen that the residual gas is measured in the same vessel in which the sample was measured before the analysis.

The final step is the estimation of this residual volume of gas as a percentage of the original volume of the sample. This is accomplished in an ingenious manner. There are two cylindrical pivoted floats, 14 and 15, in the vessel 13. Each float carries, at its lower part, an annular electrical contact which forms part of an electric circuit, indicated on the diagram (Fig. 4). Although these floats may revolve on their pivots, as they rise or fall with the liquid, an electric contact will be made by their annular portions whenever these are allowed to touch. The annular contacts are faced with platinum. The "liquid" in which they are placed is "oil". The current which passes when the circuit is completed is only small fraction of an ampere. Therefore, the chances of "failure to connect" are very remote. The contacts are, however, readily accessible, in case of necessity. The electric circuit is controlled at another point by a contact-segment mounted on a revolving disc which is operated by the motor-driven mechanism. The electrical contact at this segment is so "timed" by the mechanism, that it occurs only during the final period of analysis, when the percentage of CO_2 is to be determined and recorded.

When, during this period, the vessel 16 is lowered, causing the residual gas to be returned from the vessel 9 into the vessel 12, for the estimation of its volume, the floats 14 and 15 each tend to follow the levels of the liquids in the respective portions of vessel 13. The float 14 will remain stationary when the residual gas has all been returned from the absorption chamber 9 to the measuring vessel 12. If the original gas contained CO_2, the residual gas will obviously be of smaller volume; consequently, the level will not fall as low as the mouth of the measuring vessel and the float 14, which forms a sort of plunger or piston in the lower part of vessel 12, will remain at a higher position.

When, now, by the continued lowering of the receiving vessel 16, the float 15, in following the level of the liquid, has come down to a point where its annular contact touches the annular contact of float 14 the electric circuit will be closed, the electromagnet 17 will be energized, and the measurement will be recorded on the paper strip 18. It will be seen that when the circuit is closed, both of the floats 14 and 15 are in stable equilibrium because the gases in vessel 12 and in vessel 13 are thus at atmospheric pressure; and the possibility of variations in consequence of errors due to barometric conditions is eliminated.

The recording mechanism, being attached to a stem, rising from float 15, moves therewith. The recording point 21 does not, however, come in contact with the paper strip until the electric circuit is closed in the manner just described. In this manner, the possibility of errors due to the friction of the recording mechanism, and the consequent liability to failure of the float 15 to follow the level of the liquid, is obviated. The weight of the float and of the recording mechanism attached thereto can be accurately counterbalanced by a counter-weight 19. The float 15 can obviously be made to rise or fall to some extent in the liquid, when in a position of equilibrium, by varying the counterweight 19. Advantage is taken of this fact, in making the initial adjustment of the float 15, so as to insure the closing of the circuit at the exact point when the levels of the liquids in vessels 12 and 13 are the same.

In practice, when the same recording apparatus is used for several boilers, the recording point and the recording strips are duplicated. Fig. 3 shows a recording apparatus capable of giving four distinct recording charts, corresponding to four different boilers. In such a case, the float 15 carries and moves four recording points instead of one. The conditions are such, however, that only one of these points can make a record at any one time. In such a case, the driving mechanism of the apparatus automatically makes an analysis for each of the four boilers in succession and makes a record of the analysis on a chart corresponding to that boiler. This is done by a train of gears so arranged that, at the end of each analysis, the "selector" is connected to the sampling pipe of a different boiler. The connections are changed successively, in such a manner, that each sampling pipe in turn becomes connected with the steam jet and with the receiving vessel 7. At the same time, the electric circuit connections with the recording magnets are changed in such a manner that the magnet of the recording apparatus corresponding to that boiler is alone in circuit. The proper coördination of all the moving devices, including the displacement of the vessels 11 and 16, the change of the valve, the change of the electrical connections, etc., is insured, as already stated, by means of positive gearing-mechanism, all driven by the same source of motive power, consisting of a small constant-speed motor, shown in the lower left hand portion of the case, in Fig. 3. In this way, it is practically impossible for any of the different operations which have been described to take place out of their proper turn, or to be " out of phase."

One of the important sources of errors of previous forms of CO_2 recording apparatus was due to the fact that the residual gas was left in the measuring chamber 12 and had to be forced out by a new sample. In this case, at the end of an analysis, the residual gas is positively forced out and the measuring chamber is, so to speak, " cleaned " by the rising of the liquid until it fills, entirely, the measuring chamber. This is done by a preliminary upward " excursion " of the displacing vessel 16 which rises for that specific purpose until the level of the liquid in vessel 12 reaches the top. The only gas that is not displaced is that in the small tube connecting with valve 8. The succeeding analysis begins by the transfer of a new sample into vessel 7, while the residue is being expelled from vessel 12. In this way, a certain amount of time is gained in getting ready for the succeeding test. The design of the treating chamber 9 is such as to reduce to a minimum the time required for the absorption of the CO_2. The recorder can make a complete analysis and record the same inside of one and one-half minutes. Therefore, a recorder serving four boilers can give a record for each of the four boilers once every six minutes or ten times per hour. If the recorder is serving only two boilers, it will give a record for each every three minutes or twenty times per hour.

It is an important advantage of this CO_2 recorder that the measurement of the gas residue does not take place in the treating vessel 9, as it does, practically, in some forms of CO_2 recorder. The present CO_2 recorder, by adhering to the Orsat principle, in this respect, and forcing back the gas residue to the measuring vessel 12 before measuring it, avoids some more or less important causes of error due to changes in the volume of the reagent solution, by reason of changes of temperature and of actual increase due to the absorption of CO_2. In such a case, the error due to a change of temperature will, obviously, be all the more important when the total quantity of solution is large. The expansion of the liquid in vessel 9, either from absorption of CO_2 or from rise of temperature, has no influence on the final result. The vessel 10 with which the vessel 9 is connected, is open to the atmosphere and, consequently, allows adjustment to be made automatically between the two vessels, for change of volume.

The external features which distinguish this recorder from all previous forms, is the liberal use which has been made of *metal* to the exclusion of *glass* in its construction. It can be said, indeed, that glass has been eliminated everywhere except where it is desirable or necessary in order to allow the operation to be *seen* at any point or at any stage.

Damper-control. Mr. Stott, himself, is authority for the statement that the efficiency of a boiler plant can be materially improved by " watching the CO_2 records ". The tests made by him, and by many others since, have shown conclusively, that the CO_2 record gives accurate information regarding the efficiency of a steam boiler. For a boiler working constantly at the highest possible theoretical efficiency, the CO_2 record would be a straight line, corresponding to a little over 20% of CO_2. In practice, such high CO_2 values are seldom attained, even momentarily. Occasionally, the records may " make a jump " to 16, 17, or even 18%; but even those results are infrequent and of very short duration, and may be considered abnormal, since they correspond to conditions of combustion which cannot be maintained for any great length of time without affecting the output, or steam-capacity, of the boiler.

The above-mentioned CO_2 record corresponds to the condition of perfect combustion, in which only the quantity of air theoretically necessary for perfect combustion is admitted into the furnace. We all know that this ideal or theoretical condition could not be satisfied in practice. There always is, and, indeed, there must always be, a certain excess of air, as there are always some parts of the fire which have a deficiency of air even when there is an excess of air in the rest of the fire. The consequence is, that, practically, the highest efficiency attainable corresponds to a CO_2 record which is seldom higher than 15%, and is usually considerably lower, being as low as 9, or even 8 per cent., in some cases. This highest attainable line depends upon the design of the boiler plant, and, especially, upon the kind and quality of coal and the way in which it is burnt. For the very lowest grades of "culm", the line of highest attainable practical efficiency probably could not be higher than 8%.

The desideratum, in any boiler plant, then, is a CO_2 record which is as nearly as possible a straight line, representing an average value of CO_2 which is as high as is consistent and possible, with the particular conditions of design and operation, for that plant. That line is the line of highest attainable efficiency for that plant; and there is a similar line for every plant. The examination of CO_2 records obtained even in those boiler plants which may be considered "well regulated" to the highest degree, indicates that the CO_2 "curve" is far from being a straight line; but shows "lapses from grace" or losses of efficiency which occur in somewhat erratic, unexpected, and oftentimes apparently unaccountable manner.

Now, what Mr. Stott means by "watching the CO_2 records", is, that the careful study of such "lapses" of the CO_2 records from the line of highest practical efficiency for that particular plant, will, in nearly all if not all cases, lead to the discovery of the reasons for them; and these reasons are almost always related to the method of firing and the damper-control. The CO_2 record, obviously, renders a great service by calling attention to discrepancies or irregularities in the method of firing or to improper methods of damper-control. When the fault is discovered and remedied, the CO_2 records bear testimony to that fact by showing a decided improvement, because the CO_2 curve does not then have so many and such large breaks or notches in it.

One of the important lessons which the CO_2 recorder has taught the boiler-room expert, is that the damper must be adjusted much more *often*, and usually much *less at a time*, than it has been hitherto, if we expect to get very near the maximum efficiency obtainable in any particular plant. In the case of boiler-plants which are operated at more or less constant load, and with automatic stokers, the damper-adjustment may not need to be so frequently changed; but, in the case of boilers which are hand-fired and which supply steam for variable loads, it sometimes seems, judging from the CO_2 records, as if the damper-adjustment ought to be changed every few moments. Even in the most favorable cases, however, it ought really be changed much more often than it is.

If we admit the necessity and desirability of frequent changes of damper-adjustment, the question of finding ways and means of doing it properly and cheaply assumes some importance. In several cases the problem has been partly solved, and with satisfactory results, by making the fireman himself watch the CO_2 records, and adjust and readjust the dampers accordingly. In some cases, in large boiler plants, it might even be profitable, to have a special attendant for the purpose of watching the CO_2 records and of adjusting and readjusting the dampers. The ideal solution of this problem is, obviously, automatic damper-control.

It being evident that automatic damper-control could render valuable service, by increasing the fuel-efficiency, in a large number of steam plants, work has been done on this problem systematically, in the last year. While it seemed simple enough to let the CO_2 recorder close an electric circuit, which would start a motor that moved the damper, yet, the solution did not prove to be quite so simple as that. The truth is, that, in this case, as in the cases of all automatic apparatus, the apparatus must be so organized that it can, if not entirely replace, at least assist, human intelligence instead of counteracting its result. There being limitations to the capabilities of automatic apparatus, as there are to the limitations of the human intelligence that is at hand in the boiler room, it is necessary to exercise great foresight and to make provision, in the automatic device, for all contingencies, even that of bringing human intelligence to the "rescue", when circumstances arise which cannot be successfully dealt with by a machine, but which require more or less prompt application and exercise of human intelligence. It is needless to say that these circumstances are of frequent occurrence in the furnace of the steam boiler, and it is obvious that an automatic device which failed to do the right thing, or which did the wrong thing, at a critical moment, would be very inadvisable, to say the least. It should be so organized that it will not, at least, put the boiler out of commission, or prevent it from doing its work, even temporarily.

The practical results which have already been obtained are satisfactory and encouraging. A detailed reference cannot be made here, at the present time, for obvious reasons. It is hoped and expected, however, that full publicity can be given to the method and the results obtainable by it, within the next few months.

DISCUSSION ON "A NEW CO_2 RECORDER", AT NEW YORK, DECEMBER 13, 1907.

A. A. Adler (by letter): The CO_2 determinations are not the only determinations to be made in the proper estimation of furnace efficiency, as a low percentage of CO_2 may be due either to too much, or too little air. When too much air is admitted through the furnace, the O determinations will show a high percentage; when too little air is admitted, the carbon burns to CO and CO_2, and no oxygen will be found in the analysis. The CO_2 recorder, therefore, only indicates that there is something wrong, and leaves it for the attendant to find the real cause.

Again there is great difficulty in obtaining the proper sample to be analyzed, and the exact location cannot be determined at random. In the opinion of the writer, it should be taken before it enters the flue on the "boiler side" of the damper, so as to eliminate the errors due to infiltration of air, when natural or induced draft are used. Frequently the infiltrated air produces combustion in the flue, when CO is present, and the temperature of the flue gas rises at the far end of the flue. Such an occurrence shows an erroneous CO_2 determination, as that combustion does not benefit the boiler.

[A report presented by the Committee on a Code of Ethics at the 24th Annual Convention of the American Institute of Electrical Engineers, Niagara Falls, N. Y., June 27, 1907.

Revised by the Committee and considered at a meeting of the Board of Directors of the Institute, at New York, August 30, 1907. Ordered printed and submitted to the membership for suggestions.]

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PROPOSED CODE OF ETHICS.

PRINCIPLES OF PROFESSIONAL CONDUCT FOR THE GUIDANCE OF THE ELECTRICAL ENGINEER.

A. General Principles.

B. Relations of the electrical engineer to his employer, customer, or client.

C. Relations of the electrical engineer to the ownership of the records of his work.

D. Relations of the electrical engineer to the public.

E. Relations of the electrical engineer to the engineering fraternity.

F. Relations of the electrical engineer to the standards of his profession.

A. General Principles.

1. In both his professional and his business relations the electrical engineer should follow strictly the same ethical principles that are recognized in the social relations of every-day life. He should consider himself personally responsible for the character of the enterprises with which he is associated professionally.

2. Before entering into professional relations, it is therefore the duty of the electrical engineer to satisfy himself that the enterprises with which he connects himself are of a legitimate character. If, after becoming associated, he finds them to be of a questionable nature he should sever his connection as soon as possible. It should not be considered an excuse that his connection extends only to legitimate engineering work.

3. An electrical engineer permitting the use of his name in any enterprise or exploitation becomes morally responsible for its character. He should therefore not allow the use of his name in connection with anything upon which he is not qualified by training and experience to exercise competent judgment.

4. The electrical engineer should take care that credit for engineering work is attributed to those who, as far as his knowledge of the matter goes, are the real authors of such work.

5. The electrical engineer should incline toward and not away from standards of all kinds, since standardization is peculiarly essential to the general progress of the profession. This applies to construction, meas-

urement and expression or nomenclature, as well as to conduct, or ethics. Even the tendency to give individuality by providing special construction may usually be avoided with advantage.

B. RELATIONS OF THE ELECTRICAL ENGINEER TO HIS EMPLOYER, CUSTOMER, OR CLIENT.

7. The electrical engineer should consider the protection of his client's interests as his first obligation, and therefore should avoid every act that would be contrary to this duty; if any other consideration such as professional obligations or restrictions interfere with his so acting, in accordance with the expectation of his client, he should inform him of the situation.

8. The electrical engineer, whether consulting, designing, or operating, may not accept financial or other compensation, directly or indirectly, from more than one side or party interested in the same matter.

9. Electrical engineers in a position to decide on the use of inventions, apparatus, etc., should not be financially interested in their use, as by receiving a royalty, etc., unless the matter is clearly understood by the client or employer

10. Electrical engineers should not accept employment while financially interested in a rival concern except with the express permission of both parties. An electrical engineer may be employed by more than one party, as in the case of a consulting engineer, when the interests of the parties do not conflict and it is understood, as is usual in such cases, that he is not expected to devote his entire time to the work of one party but is free to enter into other engagements. A consulting engineer permanently retained by a party should notify other prospective employers of this affiliation before entering into relations with them. A consulting engineer when not exclusively retained by one side may advise rival concerns, with the full knowledge of all of them and upon taking care that the interests of the parties do not conflict in the particular matter handled.

11. Operating engineers should consider themselves responsible for defects in apparatus or dangerous conditions of operation, should bring the same to the attention of their employers and insist upon the removal of the causes of danger as soon as feasible.

12. An electrical engineer should in general be considered directly responsible to his employer or client for the successful fulfilment of the work upon which he has been engaged and for its satisfactory performance as a whole. It should therefore be clearly understood at the outset just what the extent or the limitations of responsibility of the engineer are to be. Whether he has been employed merely as designer or whether he is retained to design and to superintend construction; whether to design only the chief features, or also to pass upon all details of the apparatus that is to be installed. Attention should be directed to the fact that defects in the manufacture of material or apparatus is a matter distinct from the matters of design or installation. An engineer should not be held responsible for the unsatisfactory performance of a plant resulting from defective apparatus furnished, unless he has undertaken to include this subject.

C. RELATIONS OF THE ELECTRICAL ENGINEER TO THE OWNERSHIP OF THE RECORDS OF HIS WORK:

15. If in executing his work, the electrical engineer uses data or information which are not common and public property, but which he receives, directly or indirectly from his employer, or if the problem solved by the engineer is met in the pursuit of his work for his employer, and is not of such character that his attention would have been directed to it regardless of his relations to his employer, the products of his work, in the form of inventions, plans, designs, etc., are not his private property, but the property of his employer.

16. If in the execution of the work the consulting engineer uses only his own knowledge or data or information which are public property by prior publication, etc., and receives no engineering data from his employer or customer, except performance specifications, the results of the work, such as inventions, plans, designs, etc. are the private property of the engineer, and his employer or customer is entitled to their use only in the specified case.

17. All the work done by the engineer in the form of inventions, plans, designs, etc., which are outside of the field of engineering for which his employer has retained him, are the engineer's private property.

18. When an engineer or manufacturer builds apparatus from engineering designs supplied to him by his customer, the designs remain the property of the customer and should not be duplicated for other customers without express permission. When the engineer or manufacturer and his customer are jointly to work out designs and plans or develop inventions, a clear understanding should be arrived at before the beginning of the work regarding the proportionate rights of ownership in any inventions, designs, etc., that may result, since in such case both parties should be considered to have rights therein.

19. Any engineering data or information which an electrical engineer obtains, directly or indirectly, from his employer or customer, or which he creates as a result of such information, must be considered by the engineer as confidential; and while the engineer is justified in using such data or experience in his own practice as going towards his education, the publication thereof without express permission is improper, as is also its use in producing for other parties, work that is characteristic of the original customer or employer.

20. Designs, data, records and notes made during his engagement by an engineer employed on salary under permanent engagement, and referring to his work, are his employer's property. The same matter in the case of a consulting electrical engineer paid by fee or by commission, are the property of the consulting engineer.

21. A customer, in buying apparatus, does not acquire any right in its design beyond the use in the apparatus purchased. A customer of a consulting engineer does no acquire any right to the plans made by the consulting engineer except for the specific case for which the apparatus was built or the plans made.

D. RELATIONS OF THE ELECTRICAL ENGINEER TO THE GENERAL PUBLIC.

22. The electrical engineer should endeavor to assist the public to a fair and correct general understanding ot engineering matters, spread the general knowledge of electrical engineering, and discourage wrong or exaggerated statements on engineering subjects published in the press or otherwise, especially if these statements are made for the purpose of, or may lead to inducing the public to participate in unworthy schemes.

23. Controversies on engineering questions, however, should never be carried on in the public press, but should be confined to the technical press and the engineering societies.

24. First publication of inventions or other engineering advances should not be made through the public press but rather through the engineering societies and the technical press or through trade bulletins.

25. The publications which an electrical engineer is justified in making through the public press should therefore be of a historical, educational, instructive or similar character and should not relate to controversies between engineers or on engineering questions, to new inventions, etc., nor contain technical criticisms of fellow engineers, and it should be considered unprofessional to give opinions without being fully informed on all the facts relating to the question, and on the purpose for which the opinion is asked, with a full statement of the conditions under which the opinion applies.

26. In giving expert testimony before judicial bodies, the electrical engineer should confine himself to brief and clear statements on engineering or historical facts. He should not give personal opinions without so expressly stating, and should avoid pleading on one side or the other.

E. RELATIONS OF THE ELECTRICAL ENGINEER TO THE ENGINEERING FRATERNITY.

30. The electrical engineer should take interest in and show due regard for the electrical engineering societies and the technical press, and should assist his fellow engineers by exchange of general information, experience, etc. through them.

32. He should not seek a position held by another electrical engineer.

33. Where engineering work is in charge of an electrical engineer, no other electrical engineer should undertake the work except on request of or in coöperation with the electrical engineer who had charge of the work before, unless the latter's connection with it has already terminated.

35. In engineering work in charge of a board of engineers, the respective limitations of the authority of each should be decided at the outset, and each electrical engineer should give full and complete information on his part to the other engineers and insist on this being reciprocated.

F. RELATIONS OF THE ELECTRICAL ENGINEER TO THE STANDARDS OF HIS PROFESSION.

40. The title "electrician" should be applied to those having practical training sufficient to enable them to carry on intelligently certain classes of electrical work, such as the installation of electric lights and bells, and the operation of small electric plants.

41. The title "electrical engineer" should be applied only to graduates from electrical engineering schools of recognized standing, and such men as possess an equivalent knowledge of electrical engineering. Letters usually employed to denote college degrees should be used only by those holding such degrees.

42. The title "consulting electrical engineer" should be applied only to those electrical engineers who are engaged in consulting work, and who possess such knowledge and experience in electrical engineering as would qualify them to full membership in the American Institute of Electrical Engineers.

Signed,
CHARLES P. STEINMETZ,
HAROLD W. BUCK,
SCHUYLER SKAATS WHEELER.
Chairman.
Committee on a Code of Ethics.

STANDARDIZATION RULES OF THE A. I. E. E.

New York, June 17, 1907.

Dr. Samuel Sheldon,
President, American Institute Electrical Engineers,
33 West 39th Street,
New York City.

Dear Sir:—

In accordance with a motion made by Dr. Steinmetz, and duly carried at the last Annual Convention of the Institute, at Milwaukee, the Standardization Rules have been revised in form and wording and in accordance with various suggestions received from members of the Institute. This work has been accomplished by the Standards Committee which has held monthly meetings beginning in September last.

Dr. Steinmetz' motion provided that the Standardization Rules when completed by the Committee should be submitted to the Board of Directors for final adoption and promulgation. I therefore submit the revised Standardization Rules through you to the Board of Directors, and request that they be formally approved and adopted.

Respectfully yours,
(Signed) Francis B. Crocker,
Chairman, Standards Committee.

STANDARDS COMMITTEE.

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ELIHU THOMSON, Lynn, Mass.

Approved by vote of the Board of Directors, June 21, 1907.
RALPH W. POPE,
Secretary.

New York, June 21, 1907.

STANDARDIZATION RULES

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

GENERAL PLAN.

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I. DEFINITIONS AND TECHNICAL DATA.

1 *Note*: The following definitions and classifications are intended to be practically descriptive and not scientifically rigid.

A. DEFINITIONS. CURRENTS.

2 A **Direct Current** is a unidirectional current.

3 A **Continuous Current** is a steady, or non-pulsating, direct current.

4 A **Pulsating Current** is a current equivalent to the superposition of a alternating current upon a continuous current.

5 An **Alternating Current** is a current which, when plotted, consists of half-waves of equal area in successively opposite directions from the zero line.

6 An **Oscillating Current** is a current alternating in direction, and of decreasing amplitude.

B. DEFINITIONS. ROTATING MACHINES.

7 A **Generator** transforms mechanical power into electrical power.

8 A **Direct-Current Generator** produces a direct current that may or may not be continuous.

9 An **Alternator** or **Alternating-Current Generator** produces alternating current, either single-phase or polyphase.

10 A **Polyphase Generator** produces currents differing symmetrically in phase: such as two-phase currents, in which the terminal voltages on the two circuits differ in phase by 90 degrees; or three-phase currents, in which the terminal voltages on the three circuits differ in phase by 120 degrees.

11 A **Double-Current Generator** produces both direct and alternating currents.

12 A **Motor** transforms electrical into mechanical power.

13 A **Booster** is a machine inserted in series in a circuit to change its voltage. It may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

14 A **Motor-Generator** is a transforming device consisting of a motor mechanically connected to one or more generators.

15 A **Dynamotor** is a transforming device combining both motor and generator action in one magnetic field, with two armatures; or with an armature having two separate windings and independent commutators.

16 A **Converter** is a machine employing mechanical rotation in changing electrical energy from one form into another. A converter may belong to either of several types, as follows:

17 *a*. A **Direct-Current Converter** converts from a direct current to a direct current.

18 *b*. A **Synchronous Converter** (commonly called a rotary converter) converts from an alternating to a direct current, or *vice versa*.

19 *c*. A **Motor-Converter** is a combination of an induction motor with a synchronous converter, the secondary of the former feeding the armature of the latter with current at some frequency other than the impressed frequency; *i.e.*, it is a synchronous converter concatenated with an induction motor.

20 *d*. A **Frequency-Converter** converts from an alternating-current system of one frequency to an alternating-current system of another frequency, with or without a change in the number of phases or in voltages.

21 *e*. A **Rotary Phase Converter** converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

C. DEFINITIONS. STATIONARY INDUCTION APPARATUS.

22 Stationary Induction Apparatus change electric energy to electric energy through the medium of magnetic energy. They comprise several forms, distinguished as follows:

23 *a.* In **Transformers** the primary and secondary windings are insulated from one another.

24 *b.* In **Auto-Transformers**, also called compensators, a part of the primary winding is used as a secondary winding, or conversely.

25 *c.* In **Potential Regulators** a coil is in shunt and a coil is in series with the circuit, so arranged that the ratio of transformation between them is variable at will. They are of the following three classes:

6 (*a*) **Compensator Potential Regulators** in which a number of turns of one of the coils are adjustable.

7 (*b*) **Induction Potential Regulators** in which the relative positions of the primary and secondary coils are adjustable.

28 (*c*) **Magneto Potential Regulators** in which the direction of the magnetic flux with respect to the coils is adjustable.

29 *d.* **Reactors**, or **Reactance Coils**, formerly called choking coils, are a form of stationary induction apparatus used to produce reactance or phase displacement.

D. GENERAL CLASSIFICATION OF APPARATUS.

30 **Commutating Machines.** Under this head may be classed the following: Direct-current generators; direct-current motors; direct-current boosters; motor-generators; dynamotors; converters, compensators or balancers; closed-coil arc machines, and alternating-current commutating motors.

31 Commutating machines may be further classified as follows:

32 *a.* **Direct-Current Commutating Machines**, which comprise a magnetic field of constant polarity, a closed-coil armature, and a multisegmental commutator connected therewith.

33 *b.* **Alternating-Current Commutating Machines**, which comprise a magnetic field of alternating polarity, a closed-coil armature, and a multisegmental commutator connected therewith.

34 *c.* **Synchronous Commutating Machines**, which comprise synchronous converters, motor converters and double-current generators.

35 **Synchronous Machines**, which comprise a constant magnetic field, and an armature receiving or delivering alternating-currents in synchronism with the motion of the machine; *i.e.*, having a frequency equal to the product of the number of pairs of poles and the speed of the machine in revolutions per second.

36 **Stationary Induction Apparatus**, which include transformers, autotransformers, potential regulators, and reactors or reactance coils.

37 **Rotary Induction Apparatus**, or **Induction Machines**, which include apparatus wherein the primary and secondary windings rotate with respect to each other; *i.e.*, induction motors, induction generators, frequency converters, and rotary phase converters.

38 **Unipolar** or **Acyclic Machines**, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

39 **Rectifying Apparatus, Pulsating-Current Generators.**

40 **Electrostatic Apparatus**, such as condensers, etc.

41 **Electrochemical Apparatus**, such as batteries, etc.

42 **Electrothermal Apparatus**, such as rheostats, heaters, etc.

43 **Protective Apparatus**, such as fuses, lightning arresters, etc.

44 **Luminous Sources.**

E. MOTORS. SPEED CLASSIFICATION.

45 **Motors** may, for convenience, be classified with reference to their speed characteristics as follows:

46 *a.* **Constant-speed Motors**, in which the speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

47 *b.* Multispeed Motors (two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load, such as motors with two armature windings.

48 *c.* Adjustable-speed Motors, in which the speed can be varied gradually over a considerable range; but when once adjusted remains practically unaffected by the load, such as shunt motors designed for a considerable range of field variation.

49 *d.* Varying-Speed Motors, or motors in which the speed varies with the load, decreasing when the load increases; such as series motors.

F. DEFINITION AND EXPLANATION OF TERMS.

(I) *LOAD FACTOR.*

50 The Load Factor of a machine, plant or system is the ratio of the average power to the maximum power during a certain period of time. The average power is taken over a certain interval of time, such as a day or a year, and the maximum is taken over a short interval of the maximum load within that interval.

51 In each case the interval of maximum load should be definitely specified. The proper interval is usually dependent upon local conditions and upon the purpose for which load factor is to be determined.

(II) *NON-INDUCTIVE LOAD AND INDUCTIVE LOAD.*

52 A non-inductive load is a load in which the current is in phase with the voltage across the load.

53 An inductive load is a load in which the current lags behind the voltage across the load. A load in which the current leads the voltage across the load is sometimes called an anti-inductive load.

(III) *POWER-FACTOR AND REACTIVE FACTOR.*

54 The Power-Factor in alternating-current circuits or apparatus is the ratio of the electric power in watts to the apparent power in volt-amperes. It may be expressed as follows:

$$\frac{\text{true power}}{\text{apparent power}} = \frac{\text{watts}}{\text{volt-amperes}} = \frac{\text{energy current}}{\text{total current}} = \frac{\text{energy voltage}}{\text{total voltage}}$$

55 The Reactive Factor is the ratio of the wattless volt-amperes (*i.e.*, the product of the wattless component of current by voltage, or wattless component of voltage by current) to the total amperes. It may be expressed as follows:

$$\frac{\text{wattless volt-amperes}}{\text{total volt-amperes}} = \frac{\text{wattless current}}{\text{total current}} = \frac{\text{wattless voltage}}{\text{total voltage}}$$

56 Power-Factor and Reactive Factor are related as follows: If p = power-factor, q = reactive-factor, then with sine waves of voltage and current,

$$p^2+q^2 = 1$$

With distorted waves of voltage and current,

$$p^2+q^2 = \text{ or } < 1$$

(IV) *SATURATION-FACTOR.*

57 The Saturation-Factor of a machine is the ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. The saturation factor is, therefore, a criterion of the degree of saturation attained in the magnetic circuits at any excitation selected. Unless otherwise specified, however, the saturation factor of a machine refers to the excitation existing at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

58 The Percentage of Saturation of a machine at any excitation may be found from its saturation curve of generated voltage as ordinates, against

excitation as abscissas, by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percentage, is the percentage of saturation and is independent of the scale selected for excitation and voltage. This ratio is equal to the reciprocal of the saturation-factor at the same excitation, deducted from unity. Thus, if f be the saturation factor and p the percentage of saturation ratio,

$$p = 1 - \frac{1}{f}$$

(V) *VARIATION AND PULSATION.*

59 The Variation in Prime Movers which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360°.

60 The Pulsation in Prime Movers is the ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

61 The Variation in Alternators or alternating-current circuits in general is the maximum difference in phase of the generated voltage wave from a wave of absolutely constant frequency, expressed in electrical degrees (one cycle equals 360 degrees) and may be due to the variation of the prime mover.

62 The Pulsation in Alternators or alternating-current circuits, in general, is the ratio of the difference between maximum and minimum frequency during an engine cycle to the average frequency.

63 Relation of Variation in prime mover and alternator.

64 If n = number of pairs of poles, the variation of an alternator is n times the variation of its prime mover, if direct-connected, and n/p times the variation of the prime mover if rigidly connected thereto in the velocity ratio p.

II. PERFORMANCE SPECIFICATIONS AND TESTS.

A. RATING.

65 Rating by Output. All electrical apparatus should be rated by output and not by input. Generators, transformers, etc., should be rated by electrical output: motors by mechanical output.

66 Rating in Kilowatts. Electrical power should be expressed in kilowatts, except when otherwise specified.

67 Apparent Power, Kilovolt-Amperes. Apparent power in alternating-current circuits should be expressed in kilovolt-amperes as distinguished from real power in kilowatts. When the power factor is 100 per cent., the apparent power in kilovolt-amperes is equal to the kilowatts.

68 The Rated (Full-Load) Current is that current which, with the rated terminal voltage, gives the rated kilowatts, or the rated kilovolt-amperes. In machines in which the rated voltage differs from the no-load voltage, the rated current should refer to the former.

69 Determination of Rated Current. The rated current may be determined as follows: If P = rating in watts, or apparent watts if the power factor be other than 100 per cent., and E = full-load terminal voltage, the rated current per terminal is:

70 $I = \frac{P}{E}$ in a direct-current machine or single-phase alternator.

71 $I = \frac{1}{\sqrt{3}} \frac{P}{E}$ in a three-phase alternator.

72 $I = \frac{1}{2} \frac{P}{E}$ in a two-phase alternator

73 **Normal Conditions.** The rating of machines or apparatus should be based upon certain normal conditions to be assumed as standard, or to be specified. These conditions include voltage, current, power-factor, frequency, wave shape and speed; or such of them as may apply in each particular case. Performance tests should be made under these standard conditions unless otherwise specified.

74 *a.* **Power Factor.** Alternating-current apparatus should be rated in kilowatts, at 100 per cent. power factor; *i.e.*, with current in phase with terminal voltage, unless a phase displacement is inherent in the apparatus or is specified. If a power factor other than 100 per cent. is specified, the rating should be expressed in kilovolt-amperes and power factor, at rated load.

75 *b.* **Wave Shape.** In determining the rating of alternating-current machines or apparatus, a sine wave shape of alternating current and voltage is assumed, except where a distorted wave shape is inherent to the apparatus. See Secs. 79–83.

76 **Fuses.** The rating of a fuse should be the maximum current which it will continuously carry.

77 **Circuit-Breakers.** The rating of a circuit-breaker should be the maximum current which it is designed to carry continuously.

78 *a.* **Note.** In addition thereto, the maximum current and voltage at which a fuse or a circuit-breaker will open the circuit should be specified. It is to be noted that the behavior of fuses and of circuit-breakers is much influenced by the amount of electric power available on the circuit.

B. WAVE SHAPE.

79 The **Sine Wave** should be considered as standard, except where a difference in the wave form from the sinusoidal is inherent in the operation of the apparatus.

80 A **Maximum Deviation** of the wave from sinusoidal shape not exceeding 10 per cent. is permissible, except when otherwise specified.

81 The **Deviation** of wave form from the sinusoidal is measured by determining the form by oscillograph or wave meter, computing therefrom the equivalent sine wave of equal length, superposing the latter upon the observed wave in such a manner as to give least difference, and then dividing the maximum difference at any ordinate by the maximum value of the equivalent sine wave.

82 The **Equivalent Sine Wave** is a sine wave having the same frequency and the same effective or r.m.s. (root of mean square) value as the actual wave.

83 **Non-Sine Waves.** The phase displacement between two waves which are not sine waves, is that phase displacement between their equivalent sine waves which would give the same average product of instantaneous values as the actual waves; *i.e.*, the same electro-dynamometer reading.

C. EFFICIENCY.

(I) *DEFINITIONS.*

84 The **Efficiency** of an apparatus is the ratio of its net power output to its gross power input.

85 *a.* **Note.** An exception should be noted in the case of storage batteries or apparatus for storing energy in which the efficiency, unless otherwise qualified, should be understood as the ratio of the energy output to the energy intake in a normal cycle. An exception should also be noted in the case of luminous sources.

86 **Apparent Efficiency.** In apparatus in which a phase displacement is inherent to their operation, apparent efficiency should be understood as the ratio of net power output to volt-ampere input.

87 *a.* **Note.** Such apparatus comprise induction motors, reactive synchronous converters, synchronous converters controlling the voltage of an alternating-current system, self-exciting synchronous motors, potential regulators and open magnetic circuit transformers, etc.

88 *b.* **Note.** Since the apparent efficiency of apparatus delivering electric power depends upon the power-factor of the load, the apparent efficiency, unless otherwise specified, should be referred to a load power-factor of unity.

(II) *DETERMINATION OF EFFICIENCY.*

89 Methods. Efficiency may be determined by either of two methods, viz.: by measurement of input and output; or, by measurement of losses.

90 *a.* Method of Input and Output. The input and output may both be measured directly. The ratio of the latter to the former is the efficiency.

91 *b.* Method by Losses. The losses may be measured either collectively or individually. The total losses may be added to the output to derive the input, or subtracted from the input to derive the output.

92 Comparison of Methods. The output and input method is preferable with small machines. When, however, as in the case of large machines, it is impracticable to measure the output and input; or when the percentage of power loss is small and the efficiency is nearly unity, the method of determining efficiency by measuring the losses should be followed.

93 Electric Power should be measured at the terminals of the apparatus. In tests of polyphase machines, the measurement of power should not be confined to a single circuit but should be extended to all the circuits in order to avoid errors of unbalanced loading.

94 Mechanical Power in machines should be measured at the pulley, gearing, coupling, etc., thus excluding the loss of power in said pulley, gearing or coupling, but including the bearing friction and windage. The magnitude of bearing friction and windage may be considered, with constant speed, as independent of the load. The loss of power in the belt and the increase of bearing friction due to belt tension should be excluded. Where, however, a machine is mounted upon the shaft of a prime mover, in such a manner that it cannot be separated therefrom, the frictional losses in bearings and in windage, which ought, by definition, to be included in determining the efficiency, should be excluded, owing to the practical impossibility of determining them satisfactorily.

95 In Auxiliary Apparatus, such as an exciter, the power lost in the auxiliary apparatus should not be charged to the principal machine, but to the plant consisting of principal machine and auxiliary apparatus taken together. The plant efficiency in such cases should be distinguished from the machine efficiency.

96 Normal Conditions. Efficiency tests should be made under normal conditions herein set forth and which are to be assumed as standard. These conditions include voltage, current, power-factor, frequency, wave shape, speed and barometric pressure, temperature, or such of them as may apply in each particular case. Performance tests should be made under these standard conditions unless otherwise specified. See Secs. 73-75.

97 *a.* Temperature. The efficiency of all apparatus, except such as may be intended for intermittent service, should be either measured at, or reduced to, the temperature which the apparatus assumes under continuous operation at rated load, referred to a room temperature of 25° C. See Secs. 267-292.

98 With apparatus intended for intermittent service, the efficiency should be determined at the temperature assumed under specified conditions.

99 *b.* Power Factor. In determining the efficiency of alternating-current apparatus, the electric power should be measured when the current is in phase with the voltage, unless otherwise specified, except when a definite phase difference is inherent in the apparatus, as in induction motors, induction generators, frequency converters, etc.

100 *c.* Wave Shape. In electrical apparatus, the sine wave should be considered as standard, except where a difference in the wave form from the sinusoidal is inherent in the operation of the apparatus. See Secs. 79-83.

(III) *MEASUREMENT OF LOSSES.*

101 Losses. The usual sources of losses in electrical apparatus and the methods of determining these losses are as follows:

102 (*A*) Bearing Friction and Windage.

The magnitude of bearing friction and windage (which may be considered as independent of the load) is conveniently measured by driving the machine from an independent motor, the output of which may be suitably determined. See Sec. 94.

(*B*) Commutator Brush Friction.

103 The magnitude of the commutator brush friction (which may be considered as independent of the load) is determined by measuring the difference in power required for driving the machine with brushes on and with brushes off (the field being unexcited).

(*C*) Collector-Ring Brush Friction.

104 Collector-ring brush friction may be determined in the same manner as commutator brush friction. It is usually negligible.

(*D*) Molecular Magnetic Friction and Eddy Currents.

105 These losses include those due to molecular magnetic friction and eddy currents in iron and copper and other metallic parts, also the losses due to currents in the cross-connections of cross-connected armatures.

106 In Machines these losses should be determined on open circuit and at a voltage equal to the rated voltage $+I\,r$ in a generator, and $-I\,r$ in a motor, where I denotes the current strength and r denotes the internal resistance of the machine. They should be measured at the correct speed and voltage, since they do not usually vary in any definite proportion to the speed or to the voltage.

107 Note. The Total Losses in bearing friction and windage, brush friction, magnetic friction and eddy currents can, in general, be determined by a single measurement by driving the machine with the field excited, either as a motor, or by means of an independent motor.

108 Retardation Method. The no-load iron, friction, and windage losses may be segregated by the Retardation Method, in which the generator should be brought up to full speed (or, if possible, to about 10 per cent. above full speed) as a motor, and, after cutting off the driving power and excitation, frequent readings should be taken of speed and time, as the machine slows down, from which a speed-time curve can be plotted. A second curve should be taken in the same manner, but with full field excitation; from the second curve the iron losses may be found by subtracting the losses found in the first curve.

109 The speed-time curves can be plotted automatically by belting a small separately excited generator (say 1/10 kw.) to the generator shaft and connecting it to a recording voltmeter. When the retardation method is not feasible, the frictional losses in bearings and in windage, which ought, by definition, to be included in determining the efficiency, may be excluded; but this should be expressly stated.

(*E*) Armature-Resistance Loss.

110 This loss may be expressed by $p\,I^2\,r$; where r = resistance of one armature circuit or branch, I = the current in such armature circuit or branch, and p = the number of armature circuits or branches.

(*F*) Commutator Brush and Brush-Contact Resistance Loss.

111 It is desirable to point out that with carbon brushes these losses may be considerable in low-voltage machines.

(*G*) Collector-Ring and Brush-Contact Resistance Loss.

112 This loss is usually negligible, except in machines of extremely low voltage or in unipolar machines.

(*H*) Field Excitation Loss.

113 With separately excited fields, the loss of power in the resistance of the field coils alone should be considered. With either shunt- or series-field windings, however, the loss of power in the accompanying rheostat should also be included, the said rheostat being considered as an essential part of the machine, and not as separate auxiliary apparatus.

114 (*I*) Load Losses.

The load losses may be considered as the difference between the total losses under load and the sum of the losses above specified.

115 *a.* In Commutating Machines of small field distortion, the load losses are usually trivial and may, therefore, be neglected. When, however, the field distortion is large, as is shown, for instance, by the necessity for shifting the brushes between no load and full load, or with variations of load, these load losses may be considerable, and should be taken into account. In this case the efficiency may be determined either by input and output measurements, or the load losses may be estimated by the method of Sec. 116.

116 *b.* Estimation of Load Losses. While the load losses cannot well be determined individually, they may be considerable and, therefore, their joint influence should be determined by observation. This can be done by operating the machine on short-circuit and at full-load current, that is, by determining what may be called the "short-circuit core loss." With the low field intensity and great lag of current existing in this case, the load losses are usually greatly exaggerated.

117 One-third of the short-circuit core loss may, as an approximation, and in the absence of more accurate information, be assumed as the load loss.

(IV) *EFFICIENCY OF DIFFERENT TYPES OF APPARATUS.*

(*A*) Direct-Current Commutating Machines.

118 In Direct-Current Commutating Machines the losses are:

119 *a.* Bearing Friction and Windage. See Measurement of Losses (*A*), Sec. 102.

120 *b.* Molecular Magnetic Friction and Eddy Currents. See Measurement of Losses (*D*), Sec. 105.

121 *c.* Armature Resistance Losses. See Measurement of Losses (*E*), Sec. 110.

122 *d.* Commutator Brush Friction. See Measurement of Losses (*B*), Sec. 103.

123 *e.* Commutator Brush and Brush Contact Resistance. See Measurement of Losses (*F*), Sec. 111.

124 *f.* Field Excitation Loss. See Measurement of Losses (*H*), Sec. 113.

125 *g.* Load Losses. See Measurement of Losses (*I*), Sec. 114.

126 Note. *b* and *c* are losses in the armature or "armature losses"; *d* and *e* "commutator losses"; *f* "field losses."

(*B*) Alternating-Current Commutating Machines.

127 In Alternating-Current Commutating Machines, the losses are:

128 *a.* Bearing Friction and Windage. See Measurement of Losses (*A*), Sec. 102.

129 *b.* Rotation Loss, measured with the machine at open circuit, the brushes on the commutator, and the field excited by alternating current when driving the machine by a motor.

130 This loss includes molecular magnetic friction, and eddy currents, caused by rotation through the magnetic field, I^2r losses in cross-connections of cross-connected armatures, I^2r and other losses in armature-coils and armature-leads which are short-circuited by the brushes as far as these losses are due to rotation.

131 *c.* Alternating or Transformer Loss. These losses are measured by wattmeter in the field circuit, under the conditions of test *b*. They include molecular magnetic friction and eddy-currents due to the alternation of the magnetic field, I^2r losses in cross-connections of cross-connected armatures, I^2r and other losses in armature coil and commutator leads which are short-circuited by the brushes, as far as these losses are due to the alternation of the magnetic flux.

132 The losses in armature-coils and commutator leads short-circuited by the brushes, can be separated in *b*, and *c*, from the other losses, by running the machine with and without brushes on the commutator.

133 *d.* I^2r Loss, Other Load Losses in armature and compensating winding and I^2r loss of brushes, measured by wattmeter connected across the armature and compensating winding.

134 *e.* Field Excitation Loss. See Measurement of Losses (*H*), Sec. 113.

135 *f.* Commutator Brush-Friction, See Measurement of Losses (*B*), Sec. 103.

(*C*) SYNCHRONOUS COMMUTATING MACHINES.

136 1. In DOUBLE-CURRENT GENERATORS, the efficiency of the machine should be determined as a direct-current generator, and also as an alternating-current generator. The two values of efficiency may be different, and should be clearly distinguished.

137 2. In CONVERTERS the losses should be determined when driving the machine by a motor. These losses are:

138 *a*. BEARING FRICTION AND WINDAGE. See Measurement of Losses (*A*), Sec. 102.

139 *b*. MOLECULAR MAGNETIC FRICTION AND EDDY CURRENTS. See Measurement of losses (D) Sec. 105.

140 *c*. ARMATURE RESISTANCE LOSS. This loss in the armature is $q I^2 r$, where I = direct current in armature, r = armature resistance and q, a factor which is equal to 1.47 in single-circuit single-phase, 1.15 in double-circuit single-phase, 0.59 in three-phase, 0.39 in two-phase, and 0.27 in six-phase converters.

141 *d*. COMMUTATOR-BRUSH FRICTION. See Measurement of Losses (*B*), Sec. 103.

142 *e*. COLLECTOR-RING BRUSH FRICTION. See Measurement of Losses (*C*), Sec. 104.

143 *f*. COMMUTATOR-BRUSH AND BRUSH-CONTACT RESISTANCE LOSS. See Measurement of Losses (*F*), Sec. 111.

144 *g*. COLLECTOR-RING BRUSH-CONTACT RESISTANCE LOSS. See Measurement of Losses (*G*), Sec. 112.

145 *h*. FIELD EXCITATION LOSS. See Measurement of Losses (*H*), Sec. 109.

146 *i*. LOAD LOSSES. These can generally be neglected, owing to the absence of field distortion.

147 3. THE EFFICIENCY OF TWO SIMILAR CONVERTERS may be determined by operating one machine as a converter from direct to alternating, and the other as a converter from alternating to direct, connecting the alternating sides together, and measuring the difference between the direct-current input, and the direct-current output. This process may be modified by returning the output of the second machine through two boosters into the first machine and measuring the losses. Another modification is to supply the losses by an alternator between the two machines, using potential regulators.

(*D*) SYNCHRONOUS MACHINES.

148 In SYNCHRONOUS MACHINES the losses are:

149 *a*. BEARING FRICTION AND WINDAGE. See Measurement of Losses (*A*), Sec. 102.

150 *b*. MOLECULAR MAGNETIC FRICTION AND EDDY CURRENTS. See Measurement of Lossess (*D*), Sec. 105.

151 *c*. ARMATURE RESISTANCE LOSS. See Measurement of Losses (*E*), Sec. 110.

152 *d*. COLLECTOR-RING BRUSH FRICTION. See Measurement of Losses (*C*), Sec. 104.

153 *e*. COLLECTOR-RING BRUSH CONTACT RESISTANCE LOSS. See Measurement of Losses (*G*), Sec. 112.

154 *f* FIELD EXCITATION LOSS. See Measurement of Losses (*H*), Sec. 113.

155 *g*. LOAD LOSSES. See Measurement of Losses (*I*), Sec. 114.

(*E*) STATIONARY INDUCTION APPARATUS.

156 In STATIONARY INDUCTION APPARATUS, the losses are:

157 *a*. MOLECULAR MAGNETIC FRICTION AND EDDY CURRENTS measured at open secondary circuit, rated frequency, and at rated voltage $- I r$, where I = rated current, r = resistance of primary circuit.

158 *b*. RESISTANCE LOSSES, the sum of the $I^2 r$ losses in the primary and in the secondary windings of a transformer, or in the two sections of the coil in a compensator or auto-transformer, where I = rated current in the coil or section of coil, and r = resistance.

159 *c*. LOAD LOSSES, *i.e.*, eddy currents in the iron and especially in the copper conductors, caused by the current at rated load. For practical purposes they may be determined by short-circuiting the secondary of the transformer and impressing upon the primary a voltage sufficient to send rated load current through the transformer. The loss in the transformer under these conditions measured by wattmeter gives the load losses $+ I^2 r$ losses in both primary and secondary coils.

160 In Closed Magnetic Circuit Transformers, either of the two circuits may be used as primary when determining the efficiency.

161 In Potential Regulators, the efficiency should be taken at the maximum voltage for which the apparatus is designed, and with non-inductive load, unless otherwise specified.

(*F*) Rotary Induction Apparatus, or Induction Machines.

162 In Rotary Induction Apparatus, the losses are:

163 *a*. Bearing Friction and Windage. See Measurement of Losses (*A*), Sec. 102.

164 *b*. Molecular Magnetic Friction and Eddy Currents in iron, copper and other metallic parts; also $I^2 r$ losses which may exist in multiple-circuit windings. *a* and *b* together are determined by running the motor without load at rated voltage, and measuring the power input.

165 *c*. Primary $I^2 R$ Loss, which may be determined by measurement of the current and the resistance.

166 *d*. Secondary $I^2 R$ Loss, which may be determined as in the primary, when feasible; otherwise, as in squirrel-cage secondaries, this loss is measured as part of *e*.

167 *e*. Load Losses; *i.e.*, molecular magnetic friction, and eddy currents in iron, copper, etc., caused by the stray field of primary and secondary currents, and secondary $I^2 R$ loss when undeterminable under (*d*). These losses may for practical purposes be determined by measuring the total power, with the rotor short-circuited at standstill and a current in the primary circuit equal to the primary energy current at full load. The loss in the motor under these conditions may be assumed to be equal to the load losses $+ I^2 r$ losses in both primary and secondary coils.

(*G*) Unipolar or Acyclic Machines.

168 In Unipolar Machines, the losses are:

169 (*a*) Bearing Friction and Windage. See Measurement of Losses (*A*), Sec. 102.

170 (*b*) Molecular Magnetic Friction and Eddy Currents. See Measurement of Losses (*E*), Sec. 106.

171 (*c*) Armature Resistance Losses. See Measurement of Losses (*E*), Sec. 110.

172 (*d*) Collector Brush Friction. See Measurement of Losses (*C*), Sec. 104.

173 (*e*) Collector Brush Contact Resistance. See Measurement of Losses (*G*), Sec. 112.

174 (*f*) Field-Excitation as in Sec. 113. See Measurement of Losses (*H*), Sec. 113.

175 (*g*) Load Losses. See Measurement of Losses (*I*), Sec. 114.

(*H*) Rectifying Apparatus, Pulsating-Current Generators.

176 This Division Includes: open-coil arc machines and mechanical and other rectifiers.

177 In Rectifiers the most satisfactory method of determining the efficiency is to measure both electric input and electric output by wattmeter. The input is usually inductive, owing to phase displacement and to wave distortion. For this reason the power factor and the apparent efficiency should also be considered, since the latter may be much lower than the true efficiency. The power consumed by auxiliary devices, such as the synchronous motor or cooling devices, should be included in the electric input.

178 In Constant-Current Rectifiers, transforming from constant potential alternating to constant direct current, by means of constant-current transforming devices and rectifying devices, the losses in the transforming devices are to be included in determining the efficiency and have to be

measured when operating the rectifier, since in this case the losses may be greater than when feeding an alternating secondary circuit. In constant-current transforming devices, the load losses may be considerable, and, therefore, should not be neglected.

179 In OPEN COIL ARC MACHINES, the losses are essentially the same as in direct-current (closed coil) commutating machines. In this case, however, the load losses are usually greater, and the efficiency should preferably be measured by input- and output-test, using wattmeters for measuring the output. In alternating-current rectifiers, the output should, in general, be measured by wattmeter and not by voltmeter and ammeter, since owing to pulsation of current and voltage, a considerable discrepancy may exist between watts and volt-amperes. If, however, a direct-current and an alternating-current meter in the rectified circuit (either a voltmeter or an ammeter) give the same reading, the output may be measured by direct-current voltmeter and ammeter. The type of alternating-current instrument here referred to should indicate the effective or root-of-mean-square value and the type of direct-current instrument the arithmetical mean value, which would be zero on an alternating-current circuit.

(*I*) TRANSMISSION LINES.

180 The EFFICIENCY of transmission lines should be measured with non-inductive load at the receiving end, with the rated receiving voltage and frequency, also with sinusoidal impressed wave form, except where expressly specified otherwise, and with the exclusion of transformers or other apparatus at the ends of the line.

(*J*) PHASE-DISPLACING APPARATUS.

181 In APPARATUS PRODUCING PHASE DISPLACEMENT as, for example, synchronous compensators, exciters of induction generators, reactors, condensers, polarization cells, etc., the efficiency should be understood to be the ratio of the volt-amperes minus power loss to the volt-amperes.

182 The EFFICIENCY may be calculated by determining the losses, subtracting them from the volt-amperes, and then dividing the difference by the volt-amperes.

183 In SYNCHRONOUS COMPENSATORS and exciters of induction generators, the determination of losses is the same as in other synchronous machines.

184 In REACTORS the losses are molecular magnetic friction, eddy losses and $I^2 r$ loss. They should be measured by wattmeter. The efficiency of reactors should be determined with a sine wave of impressed voltage except where expressly specified otherwise.

185 In CONDENSERS, the losses are due to dielectic hysteresis and leakage, and should be determined by wattmeter with a sine wave of voltage.

186 In POLARIZATION CELLS, the losses are those due to electric resistivity and a loss in the electrolyte of the nature of chemical hysteresis. These losses may be considerable. They depend upon the frequency, voltage and temperature, and should be determined with a sine wave of impressed voltage, except where expressly specified otherwise.

D. REGULATION.

(I) *DEFINITIONS.*

187 DEFINITION. The regulation of a machine or apparatus in regard to some characteristic quantity (such as terminal voltage, current or speed) is the ratio of the deviation of that quantity from its normal value at rated load to the normal rated load value. The term "regulation," therefore, has the same meaning as the term "inherent regulation," occasionally used.

188 CONSTANT STANDARD. If the characteristic quantity is intended to remain constant (*e.g.*, constant voltage, constant speed, etc.) between rated load and no load, the regulation is the ratio of the maximum variation from the rated load value to the no-load value.

189 VARYING STANDARD. If the characteristic quantity is intended to vary in a definite manner between rated load and no load, the regulation is the ratio of the maximum variation from the specified condition to the normal rated-load value.

190 (*a*) NOTE. If the law of the variation (in voltage, current, speed, etc.) between rated load and no load is not specified, it should be assumed to be a simple linear relation; *i.e.*, one undergoing uniform variation between rated load and no load.

191 (*b*) NOTE. The regulation of an apparatus may, therefore differ according to its qualification for use. Thus, the regulation of a compound-wound generator specified as a constant-potential generator, will be different from that which it possesses when specified as an over-compounded generator.

192 In CONSTANT-POTENTIAL MACHINES, the regulation is the ratio of the maximum difference of terminal voltage from the rated-load value (occurring within the range from rated load to open circuit) to the rated load terminal voltage.

193 In CONSTANT-CURRENT MACHINES, the regulation is the ratio of the maximum difference of current from the rated load value (occurring within the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

194 In CONSTANT-POWER APPARATUS, the regulation is the ratio of maximum difference of power from the rated load value (occurring within the range of operation specified) to the rated power.

195 In CONSTANT-SPEED DIRECT-CURRENT MOTORS and INDUCTION MOTORS the regulation is the ratio of the maximum variation of speed from its rated load value (occurring within the range from rated load to no-load) to the rated load speed.

196 The regulation of an induction motor is, therefore, not identical with the slip of the motor, which is the ratio of the drop in speed from synchronism, to the synchronous speed.

197 In CONSTANT-POTENTIAL TRANSFORMERS, the regulation is the ratio of the rise of secondary terminal voltage from rated non-inductive load to no-load (at constant primary impressed terminal voltage) to the secondary terminal voltage at rated load.

198 In OVER-COMPOUNDED MACHINES, the regulation is the ratio of the maximum difference in voltage from a straight line connecting the no-load and rated-load values of terminal voltage as function of the load current, to the rated-load terminal voltage.

199 In CONVERTERS, DYNAMOTORS, MOTOR-GENERATORS AND FREQUENCY CONVERTERS, the regulation is the ratio of the maximum difference of terminal voltage at the output side from the rated-load voltage, to the rated-load voltage on the output side.

200 In TRANSMISSION LINES, FEEDERS, ETC., the regulation is the ratio of the maximum voltage difference at the receiving end, between rated non-inductive load and no load to the rated-load voltage at the receiving end. (with constant voltage impressed upon the sending end).

201 In STEAM ENGINES, the regulation is the ratio of the maximum variation of speed in passing slowly from rated-load to no-load (with constant steam pressure at the throttle) to the rated-load speed. For variation and pulsation see Secs. 59-64.

202 In a HYDRAULIC TURBINE or OTHER WATER-MOTOR, the regulation is the ratio of the maximum variation of speed in passing slowly from rated-load to no-load (at constant head of water; *i.e.*, at constant difference of level between tail race and head race), to the rated-load speed. For variation and pulsation see Secs. 59-64.

203 In a GENERATOR-UNIT, consisting of a generator united with a prime-mover, the regulation should be determined at constant conditions of the prime-mover; *i.e.*, constant steam pressure, head, etc. It includes the inherent speed variations of the prime-mover. For this reason the regulation of a generator-unit is to be distinguished from the regulation of either the prime-mover, or of the generator contained in it, when taken separately.

(II) *CONDITIONS FOR AND TESTS OF REGULATION.*

204 SPEED. The REGULATION OF GENERATORS is to be determined at constant speed, and of alternating apparatus at constant impressed frequency.

205 NON-INDUCTIVE LOAD. In apparatus generating, transforming or trans-

mitting alternating currents, regulation should be understood to refer to non-inductive load, that is, to a load in which the current is in phase with the e.m.f. at the output side of the apparatus, except where expressly specified otherwise.

206 Wave Form. In alternating apparatus receiving electric power, regulation should refer to a sine wave of e.m.f., except where expressly specified otherwise.

207 Excitation. In commutating machines, rectifying machines, and synchronous machines, such as direct-current generators and motors, alternating-current and polyphase generators, the regulation is to be determined under the following conditions:

(1) At constant excitation in separately excited fields.
(2) With constant resistance in shunt-field circuits, and
(3) With constant resistance shunting series-field circuits; *i.e.*, the field adjustment should remain constant, and should be so chosen as to give the required full-load voltage at full-load current.

208 Impedance Ratio. In alternating-current apparatus, in addition to the non-inductive regulation, the impedance ratio of the apparatus should be specified; *i.e.*, the ratio of the voltage consumed by the total internal impedance of the apparatus at full-load current, to its rated full-load voltage. As far as possible, a sinusoidal current should be used.

209 Computation of Regulation. When in synchronous machines the regulation is computed from the terminal voltage and impedance voltage, the exciting ampere-turns corresponding to terminal voltage plus armature-resistance-drop, and the ampere-turns at short-circuit corresponding to the armature-impedance-drop, should be combined vectorially to obtain the resultant ampere-turns, and the corresponding internal e.m.f. should be taken from the saturation curve.

E. INSULATION.

(I) *INSULATION RESISTANCE.*

210 Insulation Resistance is the ohmic resistance offered by an insulating coating, cover, material or support to an impressed voltage, tending to produce a leakage of current through the same.

211 Ohmic Resistance and Dielectric Strength. The ohmic resistance of the insulation is of secondary importance only, as compared with the dielectric strength, or resistance to rupture by high voltage. Since the ohmic resistance of the insulation can be very greatly increased by baking, but the dielectric strength is liable to be weakened thereby, it is preferable to specify a high dielectric strength rather than a high insulation resistance. The high-voltage test for dielectric strength should always be applied.

212 Recommended Value of Resistance. The insulation resistance of complete apparatus should be such that the rated voltage of the apparatus will not send more than $\frac{1}{1,000,000}$ of the rated-load current, at the rated terminal voltage, through the insulation. Where the value found in this way exceeds 1 megohm, it is usually sufficient.

213 Insulation Resistance Tests should, if possible, be made at the pressure for which the apparatus is designed.

(II) *DIELECTRIC STRENGTH.*

(*A*) Test Voltages.

214 Definition. The dielectric strength of an insulating wall coating, cover or path is measured by the voltage which must be applied to it in order to effect a disruptive discharge through the same

215 Basis for Determining Test Voltages. The test voltage which should be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the apparatus and its normal operating voltage, upon the nature of the service in which it is to be used, and the severity of the mechanical and electrical stresses to

which it may be subjected. The voltages and other conditions of test which are recommended have been determined as reasonable and proper for the great majority of cases and are proposed for general adoption, except when specific reasons make a modification desirable.

216 CONDITION OF APPARATUS TO BE TESTED. Commercial tests should, in general, be made with the completely assembled apparatus and not with individual parts. The apparatus should be in good condition and high-voltage tests, unless otherwise specified, should be applied before the machine is put into commercial service, and should not be applied when the insulation resistance is low owing to dirt or moisture. High-voltage tests should, in general, be made at the temperature assumed under normal operation. High-voltage tests considerably in excess of the normal voltages to determine whether specifications are fulfilled are admissible on new machines only.

217 POINTS OF APPLICATION OF VOLTAGE. The test voltage should be successively applied between each electric circuit and all other electric circuits including conducting material in the apparatus.

218 The FREQUENCY of the alternating-current test voltage is, in general, immaterial within commercial ranges. When, however, the frequency has an appreciable effect, as in alternating-current apparatus of high voltage and considerable capacity, the rated frequency of the apparatus should be used.

219 TABLE OF TESTING VOLTAGES. The following voltages are recommended for testing all apparatus, lines and cables, by a continued application for one minute. The test should be with alternating voltage having an effective value (or root mean square referred to a sine wave of voltage) given in the table and preferably for tests of alternating apparatus at the normal frequency of the apparatus.

	Rated Terminal Voltage of Circuit.	Rated Output.	Testing Voltage.
220	Not exceeding 400 volts	Under 10 kw	1,000 volts.
	" " "	10 kw. and over	1,500 "
	400 and over, but less than 800 volts	Under 10 kw	1,500 "
	" " " " "	10 kw. and over	2,000 "
	800 " " " 1,200 "	Any	3,500 "
	1,200 " " " 2,500 "	Any	5,000 "
	2,500 " "	Any	Double the normal rated voltages.

221 EXCEPTION.—TRANSFORMERS. Transformers having primary pressures of from 550 to 5,000 volts, the secondaries of which are directly connected to consumption circuits, should have a testing voltage of 10,000 volts, to be applied between the primary and secondary windings, and also between the primary winding and the core.

222 EXCEPTION.—FIELD WINDINGS. The tests for field windings should be based on the rated voltage of the exciter and the rated output of the machine of which the coils are a part. Field windings of synchronous motors and converters, which are to be started by applying alternating current to the armature when the field is not excited and a high voltage is induced in the field windings, should be tested at 5,000 volts.

223 RATED TERMINAL VOLTAGE.—DEFINITION. The rated terminal voltage of circuit in the above table, means the voltage between the conductors of the circuit to which the apparatus to be tested is to be connected,—for instance, in three-phase circuits the delta voltage should be taken. In the following specific cases, the rated terminal voltage of the circuit is to be determined as specified in ascertaining the testing voltage:

224 (*a*) TRANSFORMERS. The test of the insulation between the primary and secondary windings of transformers, is to be the same as that between the high-voltage windings and core, and both tests should be made simultaneously by connecting the low-tension winding and core together during the test. If a voltage equal to the specified testing voltage be induced in the high-tension winding of a transformer it may be used for insulation tests instead of an independently induced voltage. These tests should be made first with one end and then with the other end of the high-tension winding connected to the low-tension winding and to the core

225 (*b*) Constant-Current Apparatus. The testing voltage is to be based upon a rated terminal voltage equal to the maximum voltage which may exist at open or closed circuit.

226 (*c*) Apparatus in Series. For tests of machines or apparatus to be operated in series, so as to employ the sum of their separate voltages the testing voltage is to be based upon a rated terminal voltage equal to the sum of the separate voltages except where the frames of the machines are separately insulated, both from the ground and from each other, in which case the test for insulation between machines should be based upon the voltage of one machine, and the test between each machine and ground to be based upon the total voltage of the series.

(*B*) Methods of Testing.

227 Classes of Tests. Tects for dielectric strength cover such a wide range in voltage that the apparatus, methods and precautions which are essential in certain cases do not apply to others. For convenience, the tests will be separated into two classes:

228 Class 1. This class includes all apparatus for which the test voltage deos not exceed 10 kilovolts, unless the apparatus is of very large static capacity, *e.g.*, a large cable system This class also includes all apparatus of small static capacity, such as line insulators, switches and the like, for all test voltages.

229 Method of Test for Class 1. The test voltage is to be continuously applied for the prescribed interval,—(one minute unless otherwise specified). The test voltage may be taken from a constant-potential source and applied directly to the apparatus to be tested, or it may be raised gradually as specified for tests under Class 2.

230 Class 2. This class includes all apparatus not included in Class 1.

231 Method of Test for Class 2. The test voltage is to be raised to the required value smoothly and without sudden large increments and is then to be continuously applied for the prescribed interval,—(one minute, unless otherwise specified), and then gradually decreased.

232 Conditions and Precautions for Class 1 and Class 2. The following apply to all tests:

233 The Wave Shape should be approximately sinusoidal and the apparatus in the testing circuits should not materially distort this wave.

234 The Supply Circuit should have ample current-supply capacity so that the charging current which may be taken by the apparatus under test will not materially alter the wave form nor materially affect the test voltage. The circuit should be free from accidental interruptions.

235 Resistance or Inductance in series with the primary of a raising transformer for the purpose of controlling its voltage is liable seriously to affect the wave form, thereby causing the maximum value of the voltage to bear a different and unknown ratio to the root mean square value. This method of voltage adjustment is, therefore, in general, undesirable. It may be noted that if a resistance or inductance is employed to limit the current when burning out a fault, such resistance or inductance should be short circuited during the regular voltage test.

236 The Insulation under test should be in normal condition as to dryness and the temperature should when possible be that reached in normal service.

237 Additional Conditions and Precautions for Class 2. The following conditions and precautions, in addition to the foregoing, apply to tests of apparatus included in Class 2.

238 Sudden Increment of Testing Voltage on the apparatus under test should be avoided, particularly at high voltages and with apparatus having considerable capacity, as a momentarily excessive rise in testing voltage will result.

239 Sudden Variations in Testing Voltage of the circuit supplying the voltage during the test should be avoided as they are likely to set up injurious oscillation.

240 Good Connections in the circuits supplying the test voltage are essential in order to prevent injurious high frequency disturbances from being set up. When a heavy current is carried by a small water rheostat,

arcing may occur, causing high-frequency disturbances which should be carefully avoided.

241 TRANSFORMER COILS. In high-tension transformers, the low-tension coil should preferably be connected to the core and to the ground when the high-tension test is being made, in order to avoid the stress from low-tension to core, which would otherwise result through condenser action. The various terminals of each winding of the high-tension transformer under test should be connected together during the test in order to prevent undue stress on the insulation between turns or sections of the winding in case the high-voltage test causes a break-down.

(*C*) METHODS FOR MEASURING THE TEST VOLTAGE.

242 FOR MEASURING THE TEST VOLTAGE, two instruments are in common use, (1) the spark gap and (2) the voltmeter.

243 1. THE SPARK GAP is ordinarily adjusted so that it will break down with a certain predetermined voltage, and is connected in parallel with the insulation under test. It ensures that the voltage applied to the insulation is not greater than the break-down voltage of the spark gap. A given setting of the spark gap is a measure of one definite voltage, and, as its operation depends upon the maximum value of the voltage wave, it is independent of wave form and is a limit on the maximum stress to which the insulation is subjected. The spark gap is not conveniently adapted for comparatively low voltages.

244 IN SPARK-GAP MEASUREMENTS, the spark gap may be set for the required voltage and the auxiliary apparatus adjusted to give a voltage at which this spark gap just breaks down. The spark gap should then be adjusted for, say, 10 per cent. higher voltage, and the auxiliary apparatus again adjusted to give the voltage of the former breakdown, which is to be the assumed voltage for the test. This voltage is to be maintained for the required interval.

245 The SPARK POINTS should consist of new sewing needles, supported axially at the ends of linear conductors which are each at least twice the length of the gap. There should be no extraneous body near the gap within a radius of twice its length. A table of approximate striking distances is given in Appendix D. This table should be used in connection with tests made by the spark-gap methods.

246 A NON-INDUCTIVE RESISTANCE of about one-half ohm per volt should be inserted in series with each terminal of the gap so as to keep the discharge current between the limits of one-quarter ampere and 2 amperes. The purpose of the resistance is to limit the current in order to prevent the surges which might otherwise occur at the time of break-down.

247 2. The VOLTMETER gives a direct reading, and the different values of the voltage can be read during the application and duration of the test. It is suitable for all voltages, and does not introduce disturbances into the test circuit.

248 In VOLTMETER MEASUREMENTS, the voltmeter should, in general, derive its voltage from the high-tension testing circuit either directly or through an auxiliary ratio transformer. It is permissible, however, to measure the voltage at other places,—for example, on the primary of the transformer, provided the ratio of transformation does not materially vary during the test; or that proper account is taken thereof.

249 SPARK GAP AND VOLTMETER. The spark gap may be employed as a check upon the voltmeter used in high-tension tests in order to determine the transformation ratio of the transformer, the variation from the sine wave form and the like. It is also useful in conjunction with voltmeter measurements to limit the stress applied to the insulating material.

(*D*) APPARATUS FOR SUPPLYING TEST VOLTAGE.

250 The GENERATOR OR CIRCUIT supplying voltage for the test should have ample current carrying capacity, so that the current which may be taken for charging the apparatus to be tested will not materially alter the wave form nor otherwise materially change the voltage.

The TESTING TRANSFORMER should be such that its ratio of transformation does not vary more than 10 per cent. when delivering the charging current required by the apparatus under test. (This may be determined by short-circuiting the secondary or high voltage winding testing transformer and supplying 1/10 of the primary voltage to the primary under this condition. The primary current that flows under this condition is the maximum which should be permitted in regular dielectric tests.)

251 The VOLTAGE CONTROL may be secured in either of several ways, which, in order of preference, are as follows:

252 1. By generator field circuit.
253 2. By magnetic commutation.
254 3. By change in transformer ratio.
255 4. By resistance or choke coils.

256 In GENERATOR VOLTAGE CONTROL, the voltage of the generator should preferably be about its approximate normal rated-load value when the full testing voltage is attained, which requires that the ratio of the raising transformer be such that the full testing voltage is reached when the generator voltage is normal. This avoids the instability in the generator which may occur if a considerable leading current is taken from it when it has low voltage and low field current.

257 In MAGNETIC COMMUTATION, the control is effected by shunting the magnetic flux through a secondary coil so as to vary the induction through the coil and the voltage induced in it. The shunting should be effected smoothly, thus avoiding sudden changes in the induced voltage.

258 In TRANSFORMER VOLTAGE CONTROL, by change of ratio, it is necessary that the transition from one step to another be made without interruption of the test voltage, and by steps sufficiently small to prevent surges in the testing circuit. The necessity of this precaution is greater as the inductance or the static capacity of the apparatus in the testing circuit under test is greater.

259 When RESISTANCE COILS OR REACTORS are used for voltage control, it is desirable that the testing voltage should be secured when the controlling resistance or reactance is very nearly or entirely out of circuit in order that the disturbing effect upon the wave form which results may be negligible at the highest voltage.

F. CONDUCTIVITY.

260 COPPER. The conductivity of copper in electric wires and cables should not be less than 98% of Matthiessen's standard of conductivity, as defined in the Copper Wire Table of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

G. RISE OF TEMPERATURE.

(I) *MEASUREMENT OF TEMPERATURE.*

(*A*) METHODS.

261 There are two methods in common use for determining the rise in temperature, viz.: (1) by thermometer, and (2) by increase in resistance of an electric circuit.

262 1. By THERMOMETER. The following precautions should be observed in the use of thermometers:

263 *a.* PROTECTION. The thermometers indicating the room temperature should be protected from thermal radiation emitted by heated bodies, or from draughts of air or from temporary fluctuations of temperature. Several room thermometers should be used. In using the thermometer by applying it to a heated part, care should be taken so to protect its bulb as to prevent radiation from it, and, at the same time, not to interfere seriously with the normal radiation from the part to which it is applied.

264 *b.* BULB. When a thermometer is applied to the free surface of a machine, it is desirable that the bulb of the thermometer should be covered by a pad of definite area. A convenient pad may be formed of cotton waste in a shallow circular box about one and a half inches in diameter, through a slot in the side in which the thermometer bulb is inserted. An unduly large pad over the thermometer tends to interfere with the natural liberation of heat from the surface to which the thermometer is applied.

265 2. By Increase in Resistance. The resistance may be measured either by Wheatstone bridge, or by drop-of potential method. A temperature coefficient of 0.42 per cent. per degree C., from and at 0° C., may be assumed for copper.

The temperature-coefficients from and at each degree cent. between 0° C. and 50° C. are given in Appendix E. The temperature rise may be determined either (1) by dividing the percentage increase of initial resistance by the temperature-coefficient for the initial temperature expressed in per cent.; or (2) by multiplying the increase in per cent. of the initial resistance by 238.1 plus the initial temperature in degrees C., and then dividing the product by 100.

266 3. Comparison of Methods. In electrical conductors, the rise of temperature should be determined by their increase of resistance where practicable. Temperature elevations measured in this way are usually in excess of temperature elevations measured by thermometers. In very low resistance circuits, thermometer measurements are frequently more reliable than measurements by the resistance method. Where a thermometer applied to a coil or winding, indicates a higher temperature elevation than that shown by resistance measurement, the thermometer indication should be accepted.

(*B*) Normal Conditions for Tests.

267 1. Duration of Tests. The temperature should be measured after a run of sufficient duration for the apparatus to reach a practically constant temperature. This is usually from 6 to 18 hours, according to the size and construction of the apparatus. It is permissible, however, to shorten the time of the test by running a lesser time on an overload in current and voltage, then reducing the load to normal, and maintaining it thus until the temperature has become constant.

268 2. Room Temperature. The rise of temperature should be referred to the standard condition of a room temperature of 25° C.

269 Temperature Correction. If the room temperature during the test differs from 25° C., correction on account of difference in resistance should be made by changing the observed rise of temperature by one-half per cent. for each degree C. Thus with a room temperature of 35° C., the observed rise of temperature has to be decreased by 5 per cent., and with a room temperature of 15° C., the observed rise of temperature has to be increased by 5 per cent. In certain cases, such as shunt-field circuits without rheostat, the current strength will be changed by a change of room temperature. The heat-production and dissipation may be thereby affected. Correction for this should be made by changing the observed rise in temperature in proportion as the $I^2 R$ loss in the resistance of the apparatus is altered owing to the difference in room temperature.

270 3. Barometric Pressure. Ventilation. A barometric pressure of 760 mm. and normal conditions of ventilation should be considered as standard, and the apparatus under test should neither be exposed to draught nor enclosed, except where expressly specified. The barometric pressure needs to be considered only when differing greatly from 760 mm.

271 Barometric Pressure Correction. When the barometric pressure differs greatly from the standard pressure of 760 mm. of mercury, as at high altitudes, a correction should be applied. In the absence of more accurate data, a correction of 1% of the observed rise in temperature for each 10 mm. deviation from the 760 m.m. standard is recommended. For example at a barometric pressure of 680 mm. the observed rise of temperature is to be reduced by $\frac{760-680}{10} = 8\%$

(II) *LIMITING TEMPERATURE RISE.*

272 General. The temperature of electrical machinery under regular service conditions, should never be allowed to remain at a point at which permanent deterioration of its insulating material takes place.

273 Limits Recommended. It is recommended that the following maximum

values of temperature elevation, referred to a standard room temperature of 25 degrees centigrade, at rated load under normal conditions of ventilation or cooling, should not be exceeded.

(*A*) Machines in General.

274 In commutating machines, rectifying machines, pulsating-current generators, synchronous machines, synchronous commutating machines and unipolar machines, the temperature rise in the parts specified should not exceed the following:

275 Field and armature, 50° C.

276 Commutator and brushes, by thermometer, 55° C.

277 Collector rings, 65° C.

278 Bearings and other parts of machine, by thermometer, 40° C.

279 (*B*) Rotary Induction Apparatus. The temperature rise should not exceed the following:

280 Electric circuits, 50° C., by resistance.

281 Bearings and other parts of the machine 40° C., by thermometer.

282 In squirrel-cage or short-circuited armatures, 55° C., by thermometer, may be allowed.

(*C*) Stationary Induction Apparatus.

283 *a.* Transformers for Continuous Service. The temperature rise should not exceed 50 degrees centigrade in electric circuits, by resistance; and in other parts, by thermometer.

284 *b.* Transformers for Intermittent Service. In the case of transformers intended for intermittent service, or not operating continuously at rated load, but continuously in circuit, as in the ordinary case of lighting transformers, the temperature elevation above the surrounding air-temperature should not exceed 50° C., by resistance in electric circuits and by thermometer in other parts, after the period corresponding to the term of rated load. In this instance, the test load should not be applied until the transformer has been in circuit for a sufficient time to attain the temperature elevation due to core loss. With transformers for commercial lighting, the duration of the rated-load test may be taken as three hours, unless otherwise specified.

285 *c.* Reactors, induction- and magneto-regulators—electric circuits by resistance and other parts by thermometer, 50° C.

286 *a.* Large Apparatus. Large generators, motors, transformers, or other apparatus in which reliability and reserve overload capacity are important, are frequently specified not to rise in temperature more than 40 degrees centigrade under rated load and 55 degrees centigrade at rated overload. It is, however, ordinarily undesirable to specify lower temperature elevations than 40 degrees centigrade at rated load, measured as above.

(*D*) Rheostats.

287 In Rheostats, Heaters and other electrothermal apparatus, no combustible or inflammable part or material, or portion liable to come in contact with such material, should rise more than 50° C. above the surrounding air under the service conditions for which it is designed.

288 *a.* Parts of Rheostats. Parts of rheostats and similar apparatus rising in temperature, under the specified service conditions, more than 50° C., should not contain any combustible material, and should be arranged or installed in such a manner that neither they, nor the hot air issuing from them, can come in contact with combustible material.

(*E*) Limits Recommended in Special Cases.

289 *a.* Heat Resisting Insulation. With apparatus in which the insulating materials have special heat resisting qualities a higher temperature elevation is permissible.

290 *b.* High Air Temperature. In apparatus intended for service in places of abnormally high temperature a lower temperature elevation should be specified.

291 *c.* Apparatus Subject to Overload. In apparatus which by the nature of its service may be exposed to overload, or is to be used in very high voltage circuits, a smaller rise of temperature is desirable than in apparatus not liable to overloads or in low-voltage apparatus. In apparatus built for conditions of limited space, as railway motors, a higher rise of temperature must be allowed.

292 *d.* Apparatus for Intermittent Service. In the case of apparatus intended for intermittent service, except railway motors, the temperature elevation which is attained at the end of the period corresponding to the term of rated load, should not exceed the values specified for machines in general. In such apparatus the temperature elevation, including railway motors, should be measured after operation, under as nearly as possible the conditions of service for which the apparatus is intended, and the conditions of the test should be specified.

H. OVERLOAD CAPACITIES.

293 Performance with Overload. All apparatus should be able to carry the overload hereinafter specified without serious injury by heating, sparking, mechanical weakness, etc., and with an additional temperature rise not exceeding 15° C., above those specified for rated loads, the overload being applied after the apparatus has acquired the temperature corresponding to rated load continuous operation. Rheostats to which no temperature rise limits are attached are naturally exempt from this additional temperature rise of 15° C. under overload specified in these rules.

294 Normal Conditions. Overload guarantees should refer to normal conditions of operation regarding speed, frequency, voltage, etc., and to non-inductive conditions in alternating apparatus, except where a phase displacement is inherent in the apparatus.

295 Overload Capacities Recommended. The following overload capacities are recommended:

296 *a.* Generators. Direct-current generators and alternating-current generators, 25 per cent. for two hours.

297 *b.* Motors. Direct-current motors, induction motors and synchronous motors, not including railway and other motors intended for intermittent service, 25 per cent. for two hours, and 50 per cent. for one minute.

298 *c.* Converters. Synchronous converters, 25 per cent. for two hours, 50 per cent. for one-half hour.

299 *d.* Transformers and Rectifiers. Constant-potential transformers and rectifiers, 25 per cent. for two hours; except in transformers connected to apparatus for which a different overload is guaranteed, in which case the same guarantees shall apply for the transformers as for the apparatus connected thereto.

300 *e.* Exciters. Exciters of alternators and other synchronous machines, 10 per cent. more overload than is required for the excitation of the synchronous machine at its guaranteed overload, and for the same period of time. All exciters of alternating-current, single-phase or polyphase generators should be able to give at its rated speed, sufficient voltage and current to excite the alternator, at the rated speed, to the full-load terminal voltage, at the rated output in kilovolt-amperes and with 50 per cent. power factor.

301 *f.* A Continuous-Service Rheostat, such as an armature- or field-regulating rheostat, should be capable of carrying without injury for two hours, a current 25 per cent. greater than that at which it is rated. It should also be capable of carrying for one minute a current 50 per cent. greater than its rated load current, without injury. This excess of capacity is intended for testing purposes only, and this margin of capacity should not be relied upon in the selection of the rheostat.

302 *g.* An Intermittent Service or Motor-starting Rheostat is used for starting a motor from rest and accelerating it to rated speed. Under ordinary conditions of service, and unless expressly stated otherwise, a motor is assumed to start in fifteen seconds and with 150% of rated current strength. A motor-starter should be capable of starting the motor under these conditions once every four minutes for one hour.

303 (*a*) This Test may be carried out either by starting the motor at four-minute intervals, or by placing the starter at normal temperature across the maximum voltage for which it is marked, and moving the lever uniformly and gradually from the first to the last position during a period of fifteen seconds, the current being maintained substantially constant, at said 50% excess by introducing resistance in series or by other suitable means.

304 (*b*) Other Rheostats for Intermittent-Service are employed under such special and varied conditions, that no general rules are applicable to them.

III. VOLTAGES AND FREQUENCIES.

A. VOLTAGES.

305 Direct-Current Generators. In direct-current, low-voltage generators, the following average terminal voltages are in general use and are recommended:

125 volts.	250 volts.	550 to 600 volts.

306 Low-Voltage Circuits. In direct-current and alternating-current low-voltage circuits, the following average terminal voltages are in general use and are recommended:

110 volts.	220 volts.

307 Primary Distribution Circuits. In alternating-current, constant-potential, primary-distribution circuits, an average voltage of 2,200 volts, with step-down transformer ratios 1/10 and 1/20, is in general use, and is recommended.

308 Transmission Circuits. In alternating-current constant-potential transmission circuits, the following average voltages are recommended.

6,600	11,000	22,000	33,000	44,000	66,000	88,000

309 Transformer Ratio. It is recommended that the standard transformer ratios should be such as to transform between the standard voltages above named. The ratio will, therefore, usually be an exact multiple of 5 or 10, *e. g.*, 2,200 to 11,000; 2,200 to 44,000.

310 Range in Voltage. In alternating-current generators, or generating systems, a range of terminal voltage should be provided from rated voltage at no load to 10 per cent. in excess thereof, to cover drop in transmission. If a greater range than ten per cent. is specified, the generator should be considered as special.

B. FREQUENCIES.

311 In Alternating-Current Circuits, the following frequencies are standard:

25~	60~

312 These frequencies are already in extensive use and it is deemed advisable to adhere to them as closely as possible.

IV. GENERAL RECOMMENDATIONS.

313 Name Plates. All electrical apparatus should be provided with a name plate giving the manufacturer's name, the voltage and the current in amperes for which it is designed. Where practicable, the kilowatt capacity, character of current, speed, frequency, type, designation and serial number should be added.

314 Diagrams of Connections. All electrical apparatus when leaving the factory should be accompanied by a diagram showing the electrical connections and the relation of the different parts in sufficient detail to give the necessary information for proper installation.

315 Rheostat Data. Every rheostat should be clearly and permanently marked with the voltage and amperes, or range of amperes, for which it is designed.

316 Colored Indicating Lights. When using colored indicating lights on switch-boards, red should denote danger such as " switch closed," or " circuit alive "; green should denote safety, such as " switch open," or " circuit dead."

317 When white lights are used a light turned on should denote "danger," such as "switch closed" or "circuit alive"; while the light out should denote safety such as "switch open," or "circuit dead." Low-efficiency lamps should be used

318 The use of colored lights is recommended. as safer than white lights.

319 GROUNDING METAL WORK It is desirable that all metal work near high potential circuits be grounded

320 CIRCUIT OPENING DEVICES The following definitions are recommended.

321 *a.* A CIRCUIT-BREAKER is an apparatus for breaking a circuit at the highest current which it may be called upon to carry.

322 *b.* A DISCONNECTING SWITCH is an apparatus designed to open a circuit only when carrying little or no current.

323 *c.* An AUTOMATIC CIRCUIT-BREAKER is an apparatus for breaking a circuit automatically under an excessive strength of current. It should be capable of breaking the circuit repeatedly at rated voltage and at the maximum current which it may be called upon to carry.

V. APPENDICES AND TABULAR DATA.

APPENDIX A. NOTATION.

The following notation is recommended:

324 E, e, voltage, e.m.f., potential difference
I, i, current
P, power
Φ, magnetic flux
$\mathcal{B}$, B, magnetic density
R, r, resistance
x, reactance
Z, z, impedance
L, l, inductance
C, c, capacity
Y, y, admittance
b, susceptance
G, g, conductance
Vector quantities when used should be denoted by capital italics.

APPENDIX B.—RAILWAY MOTORS.

(I) *RATING.*

325 INTRODUCTORY NOTE ON RATING. Railway motors usually operate in a service in which both the speed and the torque developed by the motor are varying almost continually. The average requirements, however, during successive hours in a given class of service are fairly uniform. On account of the wide variation of the instantaneous loads, it is impracticable to assign any simple and definite rating to a motor which will indicate accurately the absolute capacity of a given motor or the relative capacity of different motors under service conditions. It is also impracticable to select a motor for a particular service without much fuller data with regard both to the motor and to the service than is required, for example, in the case of stationary motors which run at constant speeds.

326 SCOPE OF NOMINAL RATING. It is common usage to give railway motors a nominal rating in horse power on the basis of a one-hour test. As above explained, a simple rating of this kind is not a proper measure of service capacity. This nominal rating, however, indicates approximately the maximum output which the motor should ordinarily be called upon to develop during acceleration. Methods of determining the continuous capacity of a railway motor for service requirements are given under a subsequent heading.

327 The NOMINAL RATING of a railway motor is the horse-power output at the car-axle, that is, including gear and other transmission losses, which gives a rise of temperature above the surrounding air (referred to a room

temperature of 25 degrees cent.) not exceeding 90 degrees cent. at the commutator and 75 degrees Cent. at any other part after one hour's continuous run at its rated voltage (and frequency, in the case of an alternating-current motor) on a stand, with the motor-covers removed, and with natural ventilation. The rise in temperature is to be determined by thermometer, but the resistance of no electrical circuit in the motor shall increase more than 40% during the test.

(II) *SELECTION OF MOTOR FOR SPECIFIED SERVICE.*

328 General Requirements. The suitability of a railway motor for a specified service depends upon the following considerations:

329 *a*. Mechanical ability to develop the requisite torque and speeds as given by its speed-torque curve.

330 *b*. Ability to commutate successfully the current demanded.

331 *c*. Ability to operate in service without occasioning a temperature rise in any part which will endanger the life of the insulation.

332 Operating Conditions, Typical Run. The operating conditions which are important in the selection of a motor include the weight of load, the schedule speed, the distance between stops, the duration of stops, the rate of acceleration and of braking retardation, the grades and the curves. With these data at hand, the outputs which are required of the motor may be determined, provided the service requirements are within the limits of the speed-torque curve of the motor. These outputs may be expressed in the form of curves giving the instantaneous values of current and of voltage which must be applied to the motor. Such curves may be laid out for the entire line, but they are usually constructed only for a certain average or typical run, which is fairly representative of the conditions of service. To determine whether the motor has sufficient capacity to perform the service safely, further tests or investigations must be made.

333 Capacity Test of Railway Motor in Service. The capacity of a railway motor to deliver the necessary output may be determined by measurement of its temperature after it has reached a maximum in service. If a running test cannot be made under the actual conditions of service, an equivalent test may be made in a typical run back and forth, under such conditions of schedule speed, length of run, rate of acceleration, etc., that the test cycle of motor losses and conditions of ventilation are essentially the same as would be obtained in the specified service.

334 Methods of Comparing Motor Capacity with Service Requirements. Where it is not convenient to test motors under actual service conditions or in an equivalent typical run, recourse may be had to one of the two following methods of determining temperature rise now in general use:

335 1. Method by Losses and Thermal Capacity Curves. The heat developed in a railway motor is carried partly by conduction through the several parts and partly by convection through the air to the motor-frame whence it is distributed to the outside air. As the temperature of the several parts is thus dependent not only upon their own internal losses but also upon the temperature of neighboring parts, it becomes necessary to determine accurately the actual value and distribution of losses in a railway motor for a given service and reproduce them in an equivalent test-run The results of a series of typical runs expressed in the form of thermal capacity curves will give the relation between degrees rise per watt loss in the armature and in the field for all ratios of losses between them met with in the commercial application of a given motor.

336 This method consists, therefore, in calculating the several internal motor losses in a specified service and determining the temperature rise with these losses from thermal capacity curves giving the degrees rise per watt loss as obtained in experimental track tests made under the same conditions of ventilation.

337 The following motor losses cause its heating and should be carefully determined for a given service: $I^2 R$ in the field; $I^2 R$ in the armature; $I^2 R$ in the brush contacts, core loss and brush friction.

338 The loss in the bearings (in the case of geared motors) also adds somewhat to the motor-heating, but owing to the variable nature of such losses they are generally neglected in making calculations.

339 2. Method by Continuous Capacity of Motor. The essential losses in the motor as found in the typical run, are in most cases those in the motor windings and in the core. The mean service conditions may be expressed in terms of the current which would produce the same losses in the motor windings and the voltage which, with that current, would produce the same core losses as the average in service. The continuous capacity of the motor is given in terms of the amperes which it will carry when run on a testing stand—with covers on or off, as specified—at different voltages, say, 40, 60, 80 and 100 per cent. of the rated voltage—with a temperature rise not exceeding 90 degrees at the commutator and 75 degrees at any other part, provided the resistance of no electric circuit in the motor increases more than 40 per cent. A comparison of the equivalent service conditions with the continuous capacity of the motor will determine whether the service requirements are within the safe capacity of the motor.

340 This method affords a ready means of determining whether a specified service is within the capacity of a given motor and it is also a convenient approximate method for comparing the service capacities of different motors.

APPENDIX C. PHOTOMETRY AND LAMPS.

341 Candle-Power. The luminous intensity of sources of light is expressed in candle-power. The unit of candle-power should be derived from the standards maintained by the National Bureau of Standards at Washington, D. C., which standard unit of candle-power equals 100/88 of the Hefner unit under Reichsanstalt standard conditions for the Hefner. In practical measurements seasoned and carefully standardized incandescent lamps are more reliable and accurate than the primary standard.

342 Candle-Lumen. The total flux of light from a source is equal to its mean spherical intensity multiplied by 4π. The unit of flux is called the candle-lumen. A candle lumen is the $\frac{1}{4\pi}$th part of the total flux of light emitted by a source having a mean spherical intensity of one candle-power.

343 Candle-Meter. The unit of illumination is the candle-meter. This is the normal illumination produced by one unit of candle-power at a distance of one metre.

344 *a*. Candle-Foot. Illumination is occasionally expressed in candle-feet. A candle-foot is the normal illumination produced by one unit of candle-power at a distance of one foot.

345 1 candle-foot = 10.764 candle-metres.

The use of the candle-metre unit is preferable and is recommended.

346 The Efficiency of Electric Lamps is properly stated in terms of mean spherical candle-power per watt at lamp terminals. This use of the term efficiency is to be considered as special, and not to be confused with the generally accepted definition of efficiency in Sec. 85.

347 *a*. Efficiency, Auxiliary Devices. In illuminants requiring auxiliary power-consuming devices outside of the luminous body, such as steadying resistances in constant potential arc lamps, a distinction should be made between the net efficiency of the luminous source and the gross efficiency of the lamp. This distinction should always be stated. The gross efficiency should include the power consumed in the auxiliary resistance, etc. The net efficiency should, however, include the power consumed in the controlling mechanism of the lamp itself. Comparison between such sources of light should be made on the basis of gross efficiency, since the power consumed in the auxiliary device is essential to the operation.

348 *b*. A Standard Circuit Voltage of 110 volts, or a multiple thereof may be assumed, except where expressly stated otherwise.

349 Watts per Candle. The specific consumption of an electric lamp is its watt consumption per mean spherical candle-power. "Watts per candle" is the term used commercially in connection with incandescent lamps, and denotes, watts per mean horizontal candle-power.

350 Photometric Tests in which the results are stated in candle-power should always be made at such a distance from the source of light that the latter may be regarded as practically a point. Where tests are made at shorter distances, as for example in the measurement of lamps with reflectors, the results should always be given as " apparent candle-power " at the distance employed, which distance should always be specifically stated.

351 **BASIS FOR COMPARISON.** Either the total flux of light in candle-lumens, or the mean spherical candle-power, should always be used as the basis for comparing various luminous sources with each other, unless there is a clear understanding or statement to the contrary.

352 **INCANDESCENT LAMPS, RATING.** It is customary to rate incandescent lamps on the basis of their mean horizontal candle-power; but in comparing incandescent lamps in which the relative distribution of luminous intensity differs, the comparison should be based on their total flux of light measured in lumens, or on their mean spherical candle-power.

353 The **SPHERICAL REDUCTION-FACTOR** of a lamp

$$= \frac{\text{mean spherical candle-power}}{\text{mean horizontal candle-power}}$$

354 The **TOTAL FLUX** of light in candle-lumens emitted by a lamp = $4\,\pi \times$ mean horizontal candle-power × spherical reduction-factor.

355 The **SPHERICAL REDUCTION-FACTOR** should only be used when properly determined for the particular type and characteristics of each lamp. The spherical reduction-factor permits of substantially accurate comparisons being made between the mean spherical candle-powers of different types of incandescent lamps, and may be used in the absence of proper facilities for direct measurement of mean spherical intensity.

356 "**READING DISTANCE.**" Where standard photometric measurements are impracticable, approximate measurements of illuminants such as street lamps may be made by comparing their "reading distances;" *i.e.*, by determining alternately the distances at which an ordinary size of reading print can just be read, by the same person or persons, when all other light is screened. The angle below the horizontal at which the measurement is made should be specified when it exceeds 15°.

357 In **COMPARING DIFFERENT LUMINOUS SOURCES** not only should their candle-power be compared, but also their relative form, intrinsic brilliancy, distribution of illumination and character of light.

APPENDIX D. SPARKING DISTANCES.

358 Table of Sparking Distances in Air between Opposed Sharp Needle-Points, for Various Effective Sinusoidal Voltages, in inches and in centimetres. The table applies to the conditions specified in Secs. 240-246.

359

Kilovolts Sq. Root of Mean Square	Distance.		Kilovolts Sq. Root of Mean Square	Distance.	
	Inches	Cms.		Inches	Cms.
5	0.225	0.57	140	13.95	35.4
10	0.47	1.19	150	15.0	38.1
15	0.725	1.84	160	16.05	40.7
20	1.0	2.54	170	17.10	43.4
25	1.3	3.3	180	18.15	46.1
30	1.625	4.1	190	19.20	48.8
35	2.0	5.1	200	20.25	51.4
40	2.45	6.2	210	21.30	54.1
45	2.95	7.5	220	22.35	56.8
50	3.55	9.0	230	23.40	59.4
60	4.65	11.8	240	24.45	62.1
70	5.85	14.9	250	25.50	64.7
80	7.1	18.0	260	26.50	67.3
90	8.35	21.2	270	27.50	69.8
100	9.6	24.4	280	28.50	72.4
110	10.75	27.3	290	29.50	74.9
120	11.85	30.1	300	30.50	77.4
130	12.90	32.8			

APPENDIX E. TEMPERATURE COEFFICIENTS.

360 Table of Temperature Coefficients of Resistivity in Copper at Different Initial Temperatures Centigrade.

Initial temperature cent. i	Temp. coefficient. in percent. per degree cent.	Initial temperature cent. i	Temp. coefficient. in percent. per degree cent.
0	0.4200	26	0.3786
1	0.4182	27	0.3772
2	0.4165	28	0.3758
3	0.4148	29	0.3744
4	0.4131	30	0.3730
5	0.4114	31	0.3716
6	0.4097	32	0.3702
7	0.4080	33	0.3689
8	0.4063	34	0.3675
9	0.4047	35	0.3662
10	0.4031	36	0.3648
11	0.4015	37	0.3635
12	0.3999	38	0.3622
13	0.3983	39	0.3609
14	0.3967	40	0.3596
15	0.3951	41	0.3583
16	0.3936	42	0.3570
17	0.3920	43	0.3557
18	0.3905	44	0.3545
19	0.3890	45	0.3532
20	0.3875	46	0.3520
21	0.3860	47	0.3508
22	0.3845	48	0.3495
23	0.3830	49	0.3483
24	0.3815	50	0.3471
25	0.3801		

The fundamental relation between the increase of resistance in copper and the rise of temperature may be taken as

$$R_t = R_0\,(1+0.0042\,t)$$

where R_0 is the resistance of the copper conductor at 0° C. and R_t is the corresponding resistance at t° C. This is equivalent to taking a temperature coefficient of 0.42% per deg. C. temperature rise above 0° C. For initial temperatures other than 0° C., a similar formula may be used substituting the coefficients in the above table corresponding to the actual initial temperature. The formula thus becomes at 25° C.

$$R_{i+r} = R_i\,\left(1+\frac{0.3801\,r}{100}\right)$$

where R_i is the initial resistance at 25° C. R_{i+r} the final resistance a r the temperature rise above 25° C.

In order to find the temperature rise in degrees cent. from the initial resistance R_i at the initial temperature i° C. and the final resistance R_{i+r} we may use the formula

$$r = (238.1+i)\left(\frac{R_{i+r}}{R_i}-1\right) \quad \text{degrees C.}$$

See Sec. 265.

HISTORY OF THE STANDARDIZATION RULES.

IN CONNECTION WITH THE PRESENTATION OF THE STANDARDIZATION RULES TO THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS AT THE 23D ANNUAL CONVENTION HELD AT NIAGARA FALLS, JUNE 27. 1907.

The first step taken by the Institute toward the standardization of electrical apparatus and methods was a topical discussion on "The Standardization of Generators, Motors and Transformers," which took place simultaneously in New York and Chicago on the evening of January 26, 1898. This discussion appears in the Institute TRANSACTIONS, Vol. XV, pages 3 to 32. The opinions expressed were generally favorable to the scheme of standardization of electrical appratus, although some members feared that difficulties might arise. As a result of this discussion, a Committee on Standardization was appointed by the Council of the Institute, consisting of the following members:

FRANCIS B CROCKER, *Chairman*.	
CARY T. HUTCHINSON	CHARLES P. STEINMETZ
ARTHUR E. KENNELLY	LEWIS B STILLWELL
JOHN W. LIEB, JR.	ELIHU THOMSON

After a careful consideration of the matter and consultation with the members of the Institute and interested parties generally, a "Report of the Committee on Standardization," was presented and accepted by the Institute, June 26. 1899. These original rules appeared in the Institute TRANSACTIONS. Vol. XVI, pages 255 to 268.

As a result of changes and developments in the electric art, it was subsequently found necessary to revise the original report, this work being carried out by the following Committee on Standardization:

FRANCIS B. CROCKER, *Chairman*.	
ARTHUR E. KENNELLY	CHARLES P. STEINMETZ
JOHN W. LIEB, JR.	LEWIS B STILLWELL
C. O. MAILLOUX	ELIHU THOMSON

This revised report was adopted at the 19th Annual Convention at Great Barrington, Mass., on June 20, 1902, and appears in the Institute Transactions, Vol. XIX, pages 1075 to 1092.

In consequence of still further change and development in electrical apparatus and methods, it was decided in September, 1905 that a second revision was needed, and the following Committee was appointed to do this work.

Francis B. Crocker, *Chairman.*
Arthur E. Kennelly, *Secretary.*
Henry S. Carhart
John W. Lieb, Jr.
C. O. Mailloux
Robert B. Owens
Charles F. Scott
Charles P. Steinmetz
Henry G. Stott
S. W. Stratton

This Committee held monthly meetings and carried on extensive correspondence with manufacturers, consulting and operating engineers and other interested parties, and as a result, presented its report at the 23d Annual Convention, held at Milwaukee, May 28-30, 1906. After considerable discussion the report was accepted and referred back to the Committee for amendment and rearrangement in form. It was then to be submitted to the Board of Directors for final adoption. In September, 1906, the following Standardization Committee was appointed:

Francis B. Crocker *Chairman.*
Arthur E. Kennelly, *Secretary.*
A. W. Berresford
Dugald C. Jackson
C. O. Mailloux
R. B. Owens
Charles F. Scott
Charles P. Steinmetz
Henry G. Stott
S. W. Stratton
Elihu Thomson

This Committee held monthly meetings, also sub-committee meetings, and carefully referred the rules as a whole, and each part of them, to the members of the Institute The rules were also entirely rearranged as to form, and put in shape to facilitate ready reference to them and enable future revisions to be made without breaking up the logical arrangement. Thus amended the rules were submitted to the Board of Directors and approved by it on June 21, 1907. The Board also directed that the rules should be presented, as accepted by the Board, at the Annual Convention held at Niagara Falls, June 24 to 27, 1907, which action was taken by President Sheldon on June 26, 1905. By the Constitution which went into effect on June 10, 1907, this Committee has been made a standing Committee with the title "Standards Committee," consisting of nine members.